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On the distribution of Organic Matter in the Sea-Water and in the Bottom Samples of Maizuru Bay

By

Naobumi KOSHIMIZU

Maizuru Marine Observatory

1. *Introduction*

Of late years the contaminations of the sea-water and the sea-bottom in the bay or the harbour have come into an important question on various fields of the exploitation of the coastal sea. For example, to know the content of the soluble organic products, and to know the content of the humus of the bottom sediments may be good references to the marine product industry and to the engineering work in the bay.

2. *The relation between the consumed oxygen content of $KMnO_4$ in the sample water and the consumption of the dissolved oxygen of the sea-water in situ*

It is difficult to know directly the content of the dissolved organic matter in sea-water. Then, according to the ordinary method we analysed the consumed oxygen content of $KMnO_4$ in the sample water for the content of the soluble organic matter.

In the sea-water which is a fairly alkaline solution, the same relation of the reduction of dissolved oxyen may be occurred very gradually, then the content of the consumption of the dissolved oxygen in *situ* may be proportional to the content of the soluble organic matter.

Therefore, in a wide sense, the content of the consumption of the dissolved oxygen may be assumed to be proportional to the content of the organic matter which is oxydized in the water.

Here $[O_2]_{Total}$ is the total content of the consumed oxygen of the water in natural and $[O_2]_{KMnO_4}$ is the content of the consumed oxygen of $KMnO_4$ in the alkalified sample. The unit of $[O_2]_{KMnO_4}$ was changed into the unit of cc/l in

order to agree with the unit of the saturated oxygen according to the density of oxygen 1.429 g/l.

Then, O_2' is the content of the saturated oxygen and O_2 is that of the dissolved one. So $O_2'-O_2$ is the content of the consumed oxygen in the water in natural.

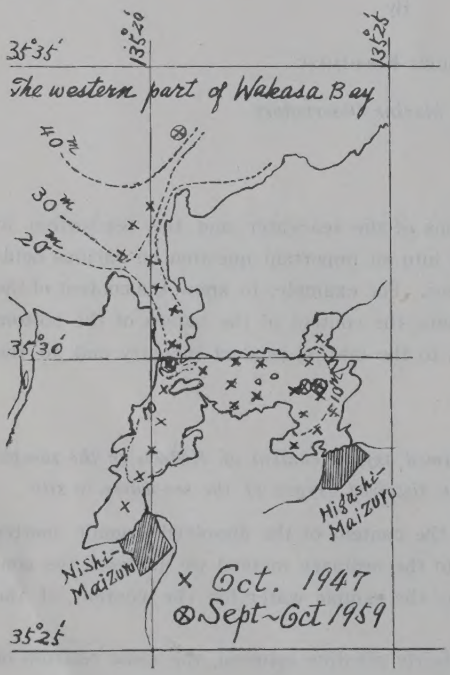

Fig 1. The stations of observations in Maizuru Bay. × shows the stations observed in October 1947, and ⊗ shows those observed with bottom sampling in September~October 1959.

The following relation may be assumed:

$$[O_2]_{Total} = [O_2]_{KMnO_4} + (O_2' - O_2)$$

3. *The results of the determination of the content of the total consumed oxygen owing to the organic matter in a wide sense in Maizuru Bay, October 1947*

On the water samples of twenty-six stations in which 0, 3, 5, 10, 15, 20, 25, and 30 m layers observed, we carried out the chemical analysis of the dissolved oxygen, the consumed oxygen in the alkalified sample, and the chlorinity. The contents of the saturated oxygen were calculated according to Fox's numerical relation.

The average contents of $[O_2]_{KMnO_4}$ and those of the sum of $[O_2]_{KMnO_4}$ and the difference between O_2' and O_2 at each layer are shown in Fig. 2.

4. *The quantitative relation between the total consumed oxygen and the organic matter of the bottle sample at each depth*

Observing the character of the sediment of the bottom sample, the sedi-

ment contains much grains or sands in the area of the depth between 0 m and 3 m, and it is the black humus mud containing the slight content of H_2S in that of the depth between 5 m and 15 m, and it is the blue-gray soft mud in that of the depth between 20 m and 30 m.

In point of the organic contamination, the character of the bottom sample appears to be well agreed with the content of the total consumed oxygen of water at each layer in Maizuru Bay. In the depth between 5 m and 15 m, the water is contaminated by the remarkable amount of organic matter because the sediment in the depth of 10 m or so appears to contain the richest soluble organic matter in the bottom of the bay as shown in Fig. 2. Then it may be possible to assume that the horizontal flowing will be predominent in the bay.

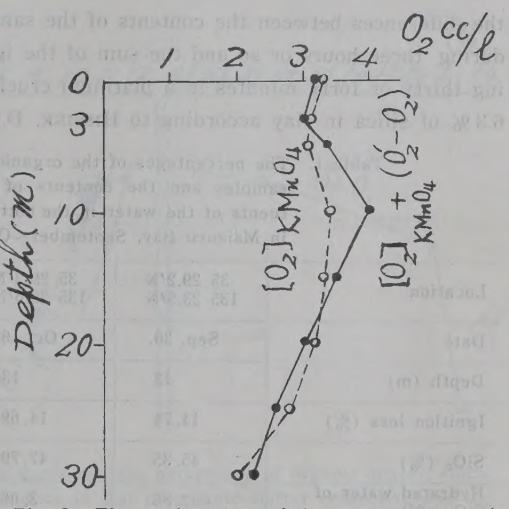

Fig. 2. The total content of the oxygen consumption (full line) which is modificated by the addition of the difference between the saturated content and the dissolved one to the content of the consumed oxygen of $KMnO_4$ (dotted line) in the each layer. Those values were calculated from the averages of twenty-six stations in Maizuru Bay, October 1947.

5. The determination of the organic matter in the bottom sample

The total consumed oxygen content owing to the soluble organic matter and the consumption of the dissolved oxygen distributes vertically as stated above. On the other hand the author carried out the chemical analysis for the determination of organic matter of the bottom samples in the end of September and in the beginning of October 1959. The season of the bottle sampling is almost same to that of the marine observation 1947.

The values of the organic matter content in Table 1 were calculated as

the differences between the contents of the samples which were dried at 110°C during three hours or so and the sum of the ignition loss at about 950°C during thirty or forty minutes in a platinum crucible and the hydrated water of 6.3% of silica in clay according to HISSINK, D.J.

Table 1. The percentages of the organic matter of the bottom samples and the contents of other chemical constituents of the water in the bottom layer at each station in Maizuru Bay, September~October 1959.

Location		35 29.2′N 135 23.5′N	35 29.3′N 135 20.6′N	35 29.8′N 135 20.6′E	35 33.7′N 135 20.5′E
Date		Sep. 30.	Oct. 6.	Sep. 30.	Sep. 29.
Depth (m)		12	13	23	48
Ignition loss (%)		14.74	14.69	14.43	12.32
SiO_2 (%)		45.35	47.79	52.38	53.30
Hydrated water of SiO_2 (%)		2.86	3.06	3.30	3.36
Organic matter (%)		11.88	11.63	11.13	8.96
Chemical constituents of the bottom water	Depth (m)	10	10	20	48
	Chlorinity (‰)	18.12	18.33	18.60	18.96
	Oxygen saturation (%)	79.51	70.17	84.33	83.87
	Si (μg-atom/L)	9	8	6	4
	P (μg-atom/L)	0.14	0.46	0.17	0.23
	Water temp. (°C)	25.10	24.37	22.70	18.46
Mud temp. (°C)		—	23.3	—	—

According to the Table 1, the values of the inside of the bay vary from 11.1 to 11.9% and that of the outside shows under 9%. The content of the organic matter decreases gradually in proportion as the observation station approaches to the mouth of the bay and decreases predominently in the outside.

6. The relation between the percentages of the organic matter in the bottom sample and the depth

The relation between the percentage of the organic matter and the depth

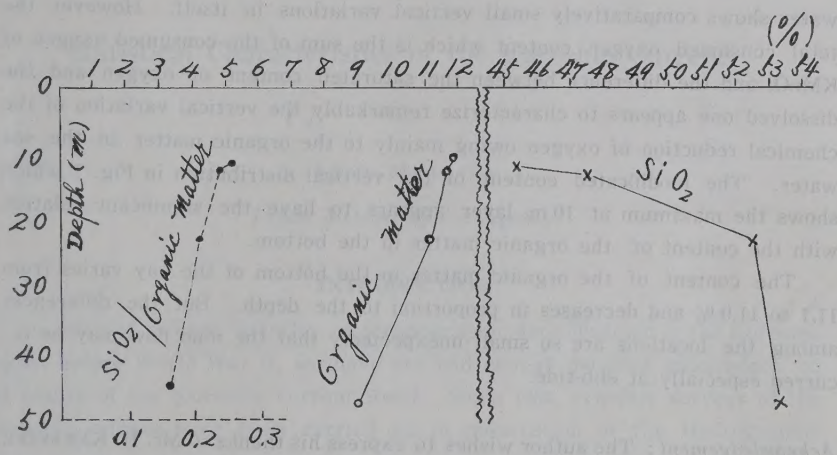

Fig. 3. The relations between the depth and the percentage of organic matter, silica, and the ratio of the content of silica to that of organic matter respectively in the bottom samples of Maizuru Bay, October 1947.

appears to be linear and the former decreases gradually with the latter. On the other hand, the percentage of silica which is the main constituent in the bottom sample increases with depth.

The ratio of the percentage of the organic matter to that of the silica shows 0.2~0.3 in the inside and 0.1~0.2 in the outside of the bay.

7. *On the mud flow in the bay*

Because of the small difference between the percentage of the organic matter of the inner part and that of the part near the entrance of the bay, the mud flow may be occurred in some degree especially at the time of ebb-tide although the bottom slope is under one degree everywhere in the bay.

Consequently the deposition of the organic matter in the bottom may be reduced in some degree owing to the mud flow.

8. *Conclusion*

The content of the consumed oxygen of $KMnO_4$ in the alkalified sample which may represent the content of the soluble organic matter in the sea

water shows comparatively small vertical variations in itself. However the total consumed oxygen content which is the sum of the consumed oxygen of $KMnO_4$ and the difference between the saturated content of oxygen and the dissolved one appears to characterize remarkably the vertical variation of the chemical reduction of oxygen owing mainly to the organic matter in the sea water. The modificated content of the vertical distribution in Fig. 1 which shows the maximum at 10 m layer appears to have the significant relation with the content of the organic matter in the bottom.

The content of the organic matter in the bottom of the bay varies from 11.1 to 11.9% and decreases in proportion to the depth. But the differences among the locations are so small unexpectedly that the mud flow may be occurred especially at ebb-tide.

Acknowledgement: The author wishes to express his thanks to Mr. H. KAWASAKI, the Chief of Maizuru Marine Observatory and Mr. T. IIDA for the usefull suggestions. The author also wishes to express his appreciation to Dr. T. KAWAMOTO who engaged with author in the chemical analysis of the water samples in that observation.

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Statistical Characteristics of the Kuroshio Current*

By

Jotaro Masuzawa

Japan Meteorological Agency

INTRODUCTION

In spite of a large quantity of oceanographic data obtained in the Kuroshio region before World War II, we have not had enough detailed knowledges on the nature of the Kuroshio current itself. Since 1954, synoptic surveys of the Kuroshio current have been carried out in cooperation of the Hydrographic

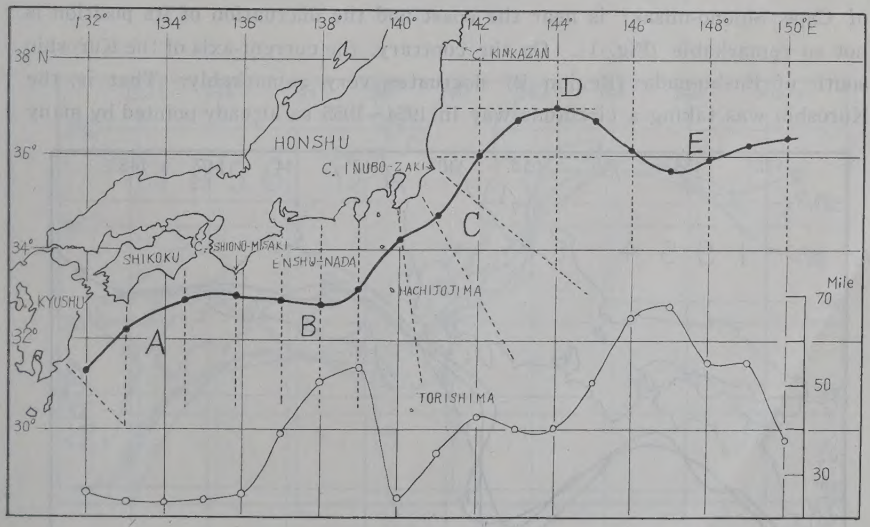

Fig. 1. Average current-axis of the Kuroshio during the period from November, 1954 to August, 1959. The lower curve shows the unbiased estimate of standard deviation of the current-axis position on each meridian. Broken lines are usual observational lines.

* Currents and Water Masses of the Kuroshio System (XI)

Office, the Kobe Marine Observatroy and the Oceanographical Section of the Japan Meteorological Agency. They consist of four times observations a year (February～March, May, August and November) with the network of almost prearranged lines across the Kuroshio (Fig. 1).

The purpose of this report is to ascertain some common knowledges on the Kuroshio and to find any new ideas on its fluctuations, from the statistical analysis of those recent data.

CURRENT PATTERN

The location of current-axis was determined by surface velocities measured with GEK and also by subsurface temperatures measured with BT. Figs. 2a～f present the current patterns south and east of Japan in the last six years (1954～1959).

The current-axis in the Region A from the south of Kyushu to the south of Cape Shiono-misaki is near the coast and the fluctuation of its position is not so remarkable (Fig. 1). On the contrary, the current-axis of the Kuroshio south of Enshu-nada (Region B) fluctuates very remarkably. That is, the Kuroshio was taking a circutous way in 1954～1955 as already pointed by many

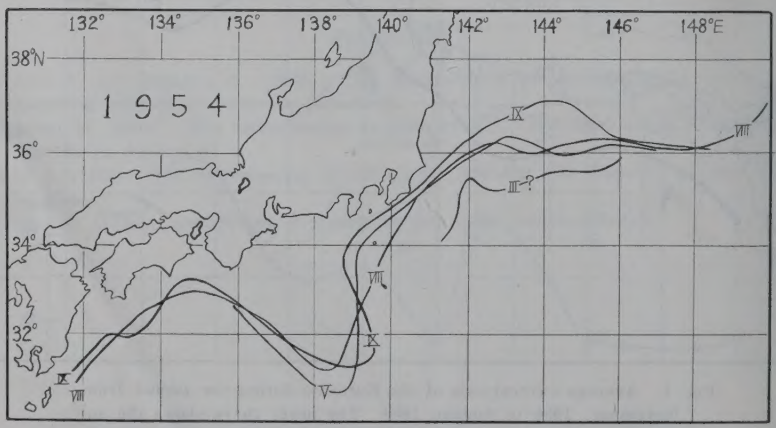

Fig. 2a

Fig. 2a-2f. Fluctuations of the Kuroshio current-axis in 1954～1959. Roman figures shows the month of observation.

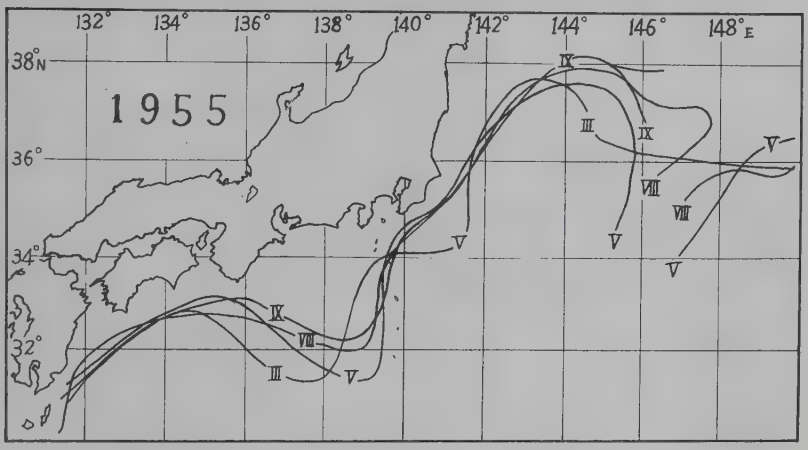

Fig. 2b

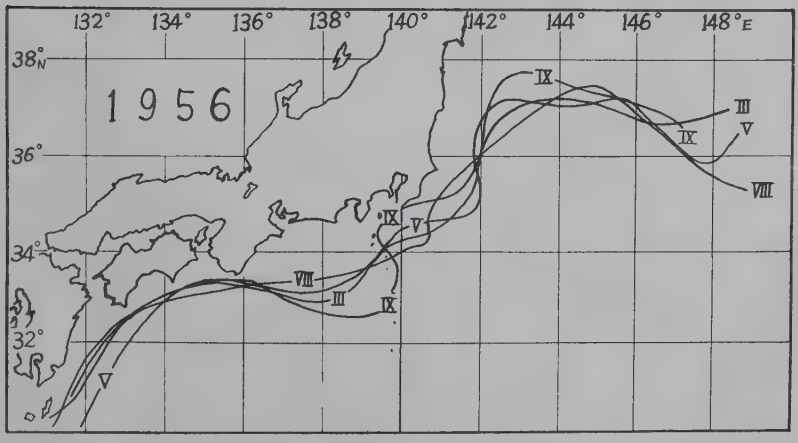

Fig. 2c

authors (for example, MORIYASU 1959). This phenomenon is supposed to have started at the middle of 1953 (MASUZAWA 1954), and it accompanied the appearance of the so-called "Cold Water Mass" at Enshu-nada. In three years

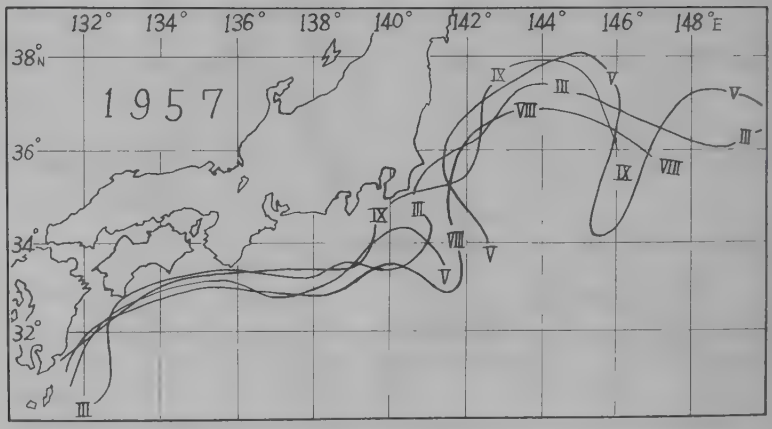

Fig. 2d

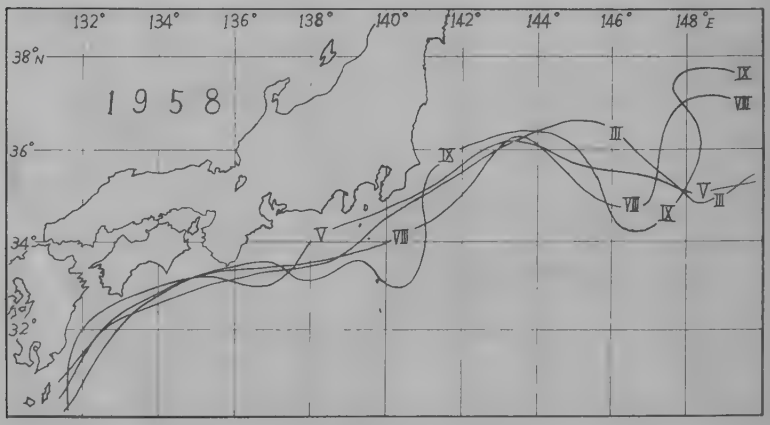

Fig. 2e

of 1956~1958 the Kuroshio was flowing almost eastwards. while at the beginning of 1959 a meandering occurred at the southeast of Kyushu and it progressed to the east in developing and since the summer there has existed at Enshu-nada

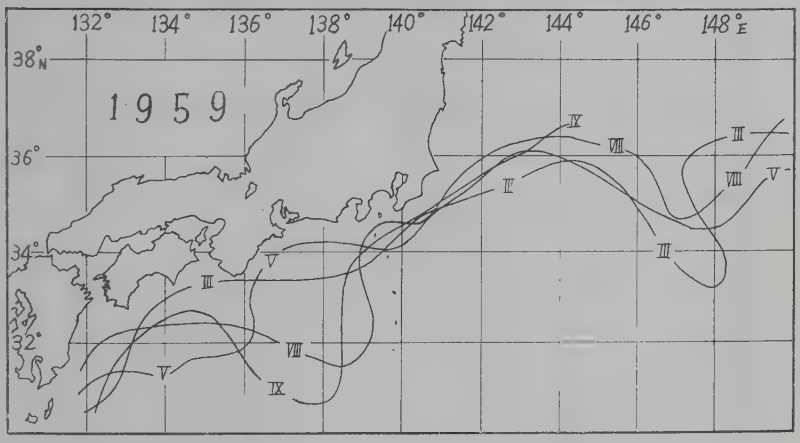

Fig. 2f

such a cold water region as seen in 1955~1956. These remarkable oceanic conditions sometimes occurred before World War II (Uda 1949). Though the mechanism of appearance or disappearance of this cold region has been discussed by many Japanese oceanographers (Uda 1949, Ichiye 1955, Fukuoka 1958 and Nan'niti 1958, etc.), we have had yet no satisfactory explanation.

In the Region **C** southeast of Cape Inubo-zaki, the fluctuation of current axis was relatively dominant in 1956~1957, when the cold region disappeared at the south of Enshu-nada. The Kuroshio east of Honshu (the Kuroshio Extension) generally shows meandering patterns. They are more remarkable at the Region **E** where the average current-axis curve is convex to the south than at the Region **D** where it is convex to the north. After the meandering had extremely developed, we often found isolated warm anticyclonic watermasses to the north, or cold cyclonic watermasses to the south of the Kuroshio current axis (Masuzawa 1957). Especially, the fluctuation at the Region **E** is very active and it seems to occur in the shorter period.

It has been already pointed out (Kawai 1955) that the current-axis at the Region **C** moves to the north or south in the period of about 4.5 years. It is found in Fig. 3 that the long-term fluctuation is more dominant than the seasonal variation, that is, the current-axis was located at the north in 1955~1957, while it was located at the south in 1958~1959. Moreover, we can re-

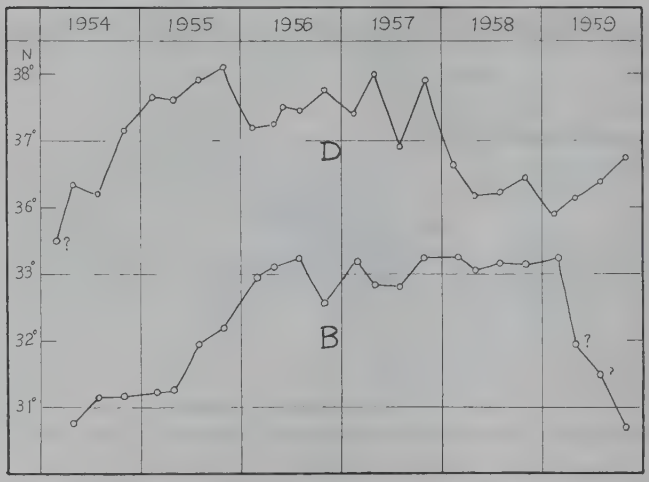

Fig. 3. The northern limit of the Kuroshio in the Region **D** and the southern one in the Region **B** (see Fig. 1).

cognize that the current-axis is at the northernmost position in autumn of all seasons. Comparing the fluctuation of the location of the current-axis at the Region **D** with the one at the Region **B**, we cannot find the precedence of the meandering states at the Region **B**.

CURRENT VELOCITY

All values of the surface maximum velocity observed at the current-axis

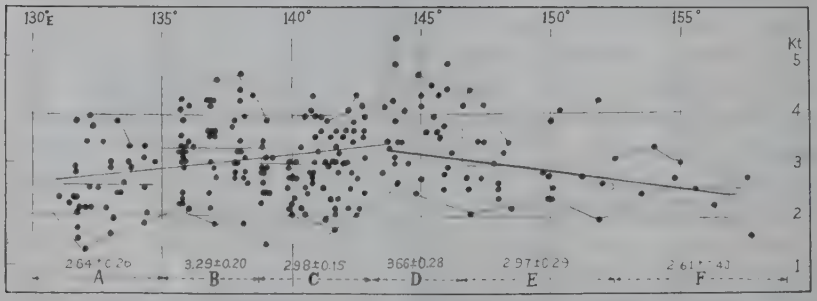

Fig. 4. The distribution of the maximum surface velocity at the Kuroshio current-axis in 1955~1959. Lower figures show average values of each Region (see Fig. 1). The confidence intervals of average are computed for the significant level of 95%.

with GEK are plotted along the current-direction of the Kuroshio in Fig. 4.

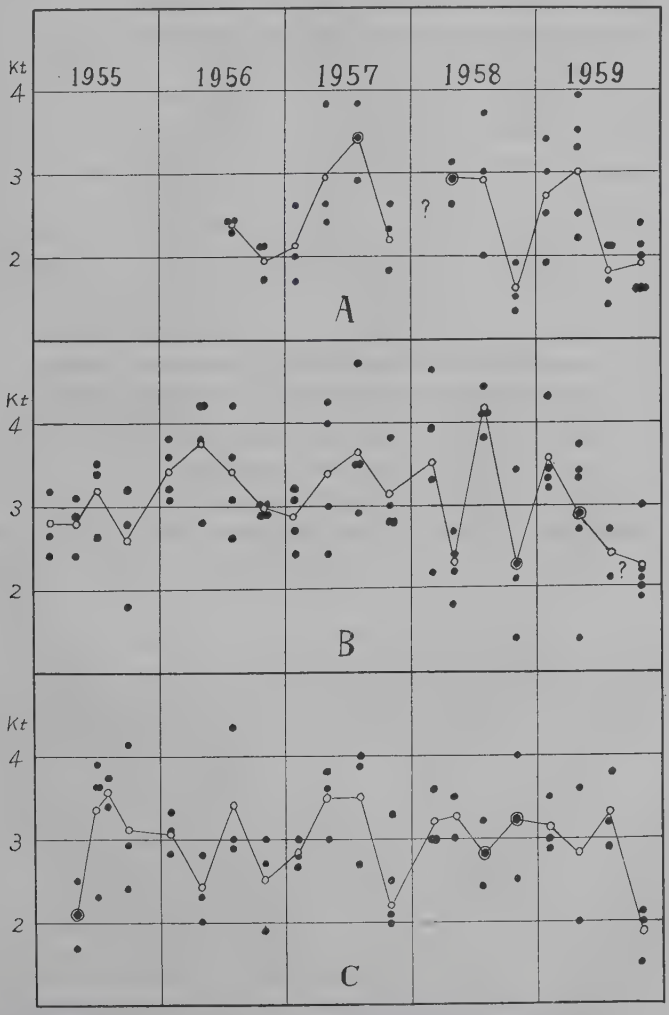

Fig. 5. Fluctuations of the maximum surface velocity at the Kuroshio current-axis south of Shikoku (A), Enshu-nada (B) and southeast of Honshu (C) (see Fig. 1). Open circles show average values at three or four sections in each Region.

The velocity at the Kuroshio current-axis is larger at the regions from Cape Shiono-misaki to 150°E longitude, largest at the Region **D**.

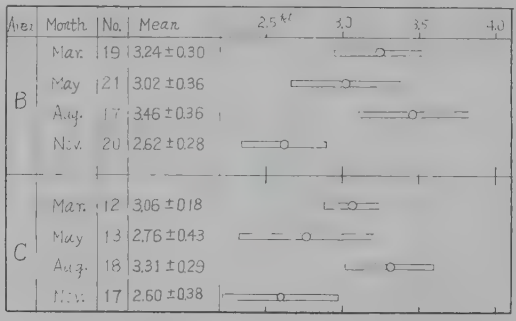

Fig. 6. Seasonal variation of maximum surface velocity of the Kuroshio current-axis south of Enshu-nada (B) and southeast of Honshu (C) in 1955～1959. The confidence intervals of average are computed for the significant level of 95%.

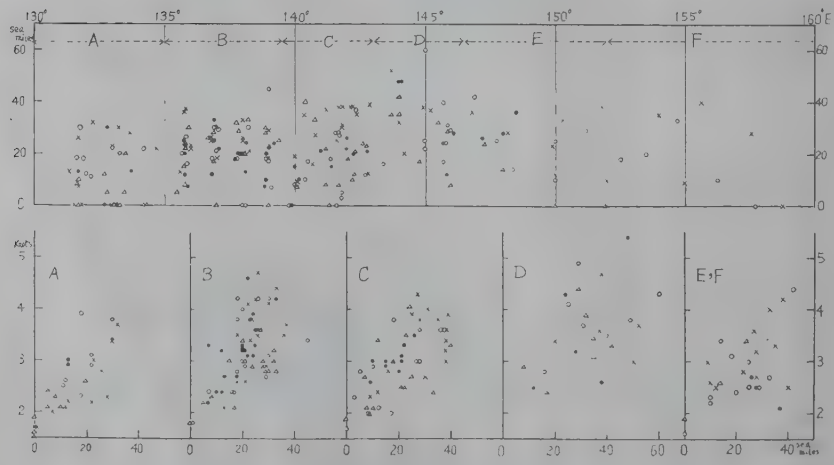

Fig. 7. Upper: The distribution of current-width of the Kuroshio (surface velocity > 2 knots). Lower: The relation-ship between the current-width and the surface maximum velocity. (•) February～March, (○) May, (×) August, (△) November.

From the most reliable data at the Regions **A**, **B** and **C** of those current velocity data, the time-changes of velocity are shown at each Region in Fig. 5. We cannot find any systematic variations such as the fluctuation of current pattern, but almost random fluctuations seem to be predominant. However, as seen in Fig. 6, the seasonal variation of velocity vaguely presents a semi-annual period, the principal maximum in summer, the secondary one in winter, the principal minimum in autumn, the secondary one in spring. But the secondary extremes are not so sure.

The width of strong current does not present any noticeable distributions along the current except the relatively large value at the Region **D** (Fig. 7). In Fig. 7 are also shown the relationships between the maximum velocity and the width of strong current. Being not so well-defined, they are very approximately a kind of proportional relationships. In other words, the maximum velocity is roughly proportional to the surface transport of the strong current. If the latter is proportional to the total transport of the Kuroshio, the maximum surface velocity will be a measure of the Kuroshio transport. If it is true, the transport of the Kuroshio would present a semi-annual variation as well as the maximum velocity. This is coincident with the result obtained by the dynamic computation in the section south of Cape Shiono-misaki (MASUZAWA, 1954).

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Plankton in the Northwestern Pacific Ocean in Summer of 1958

By

R. Marumo, M. Kitou and O. Asaoka

1. *Introduction.*

Oceanographic investigations were carried out on board the research ship Ryofu-maru of the Japan Meteorological Agency in the western part of the North Pacific Ocean in the period from July 26 to September 9, 1958, as a part of the cooperative oceanographic observations in the International Geophysical Year (Fig. 1). In the present paper, properties of plankton communities are discussed with reference to hydrographical conditions.

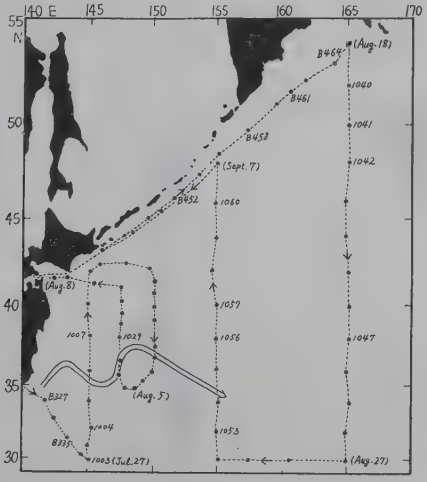

Fig. 1. Observational stations.

Because the authors intend to use frequently the terms, "warm-water species" and "cold-water species", these should be defined in the beginning. The area investigated is fairly extensive and the water temperature changes

in a wide range, for instance, between 10 and 28°C in the surface layer and between 1 and 21°C at the 100-m depth, and consequently the distributional pattern of each species is obviously drawn. The cold-water species is defined as that which occurs mainly in northern cold waters and decreases in southern warm waters. The opposite is defined as warm-water species. So far as the said area is concerned, the former may be expressed in other words as "the Oyashio species", and the latter as "the Kuroshio species". But, several species are cosmopolitan and are widely distributed both in colder and warmer waters, and a few are restricted within the transition area between the Oyashio and Kuroshio waters.

2. Collection methods.

To make a watermass analysis by means of the plankton distribution, it is desired that as many kinds of ecological groups as possible are used and the analysis is made from various standpoints. For this pourpose, the following three different methods were adopted, and diatoms, dinoflagellates, copepods and other plankton organisms were utilized.

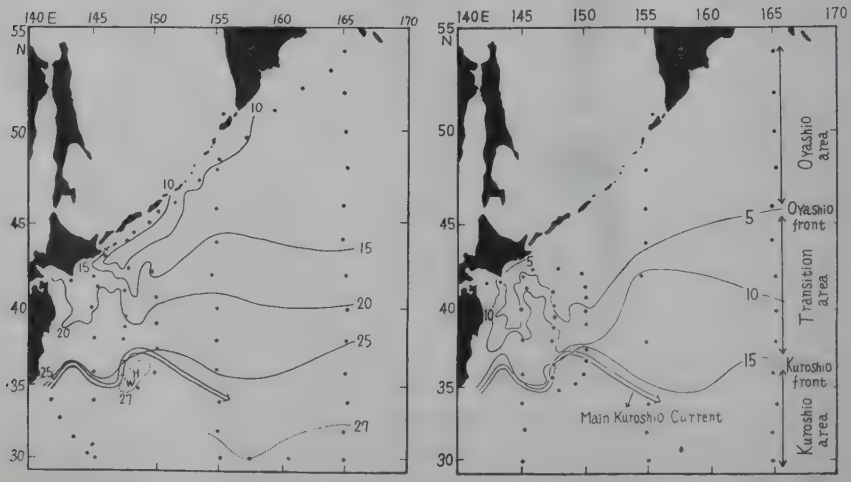

Fig. 2. Horizontal distributions of the surface (left) and 100-m (right) isotherms (°C).

(1) The filtering method.

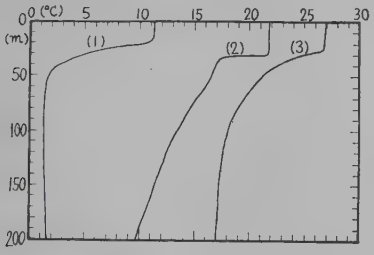

Fig. 3. Vertical distributions of water temperature obtained from BT-records. (1) St. 1060, 46°N, 155°E, in the Oyashio area, (2) St. 1057, 40°N, 155°E, in the transition area, (3) St. 1053, 32°N, 155°E, in the Kuroshio area.

About 400 liters of sea water were sucked up from the 4-m depth below the surface and plankton organisms in it were filtered with XX 13 bolting clothes. These ecological groups are effectively used for clarifying the complicated hydrographical features of the surface thin isothermal layer in the season of summer. Such plankton organisms as diatoms, dinoflagellates, tintinnods and pelagic larvae of littoral animals collected by this method are generally larger than those collected by other methods.

(2) The centrifugal method.

Water samples were obtained from the surface and from the 20-m, 50-m and 100-m depths with a bucket or Nansen bottles. Plankton organisms in 330 cc of water were fixed by picroformalin and then concentrated into several drops of water by settling and centrifuging. The microplankton distribution not only in the horizontal direction but also in the vertical is understood from these samples. Only a diatom, *Chaetoceros radicans* Schütt, is treated now. The detailed plankton data by this method have been already reported (Japan Meteorological Agency, 1959).

(3) The net method.

For zooplankton collection the Norpac Plankton Net was used in the present IGY survey. It was first used in the Norpac cooperative oceanographic investigations, as a standard type of plankton net in Japan. Its shape is conical. The size is 45 cm in mouth diameter and 180 cm in length. The filtering cloth is made of bolting silk GG 54 processed with plastics, mesh apertures being 0.33 mm. A flow-meter is fixed in the center of the mouth ring by three cotton ropes. Vertical hauls were made at a speed of about one meter per second from the 150-m depth to the surface. Determination was done on total wet weights and copepods, and the amounts were expressed for 1 cubic meter of

sea water, after they were corrected by readings of the flow-meter. Detailed net-plankton data have been reported (Japan Meteorological Agency, 1959).

3. Hydrographical conditions.

In the western part of the North Pacific Ocean, watermasses are generally arranged in the order of the Oyashio area, the transition area and the Kuroshio area from north to south (Fig. 2). According to KAWAI (1955), the boundary of the Oyashio and transition areas is named the Oyashio front and that of the Kuroshio area is named the Kuroshio front, and the situations of the Oyashio and Kuroshio fronts respectively correspond to 5 and 15°C isotherms at the 100-m depth in summer. In the summer of 1958 the Kuroshio main current was obviously recognized as far as 155°E, maintaining its speed of 2-4 knots, but it became obscure at 165°E and the current speed dropped below 1.3 knots.

There exists the surface isothermal water which is distinct from the underlying water by a remarkable thermocline (Fig. 3). On the basis of BT-records, the depth of this layer is about 10 m in the Oyashio area and 20-30 m in the Kuroshio area. The surface water is influenced by violent meteorological phenomena such as solar radiation, rainfall, evaporation etc. in summer, and consequently it seems that its physical and chemical properties in origin are to a great extent lost. Analysis of such a peculiar water will be made more effectively by means of plankton than by hydrographical elements such as water temperature and chlorinity.

4. Plankton collected by the filtering method.

In this chapter, explanation is made on the geographical distributions of diatoms, dinoflagellates, tintinnods etc. treated by the filtering method, and characters of the surface water are ascertained from these distributions.

(1) Diatoms.

As for the cell number, diatoms are abundant in the northern area and scarce in the southern area and the population pattern is generally distributed in parallel with isotherms (Fig. 4). The densest zone along the Kurile Islands is occupied by a remarkable neritic community. At station B327 near the coast in the Kuroshio area the cell number is largest in this investigation,

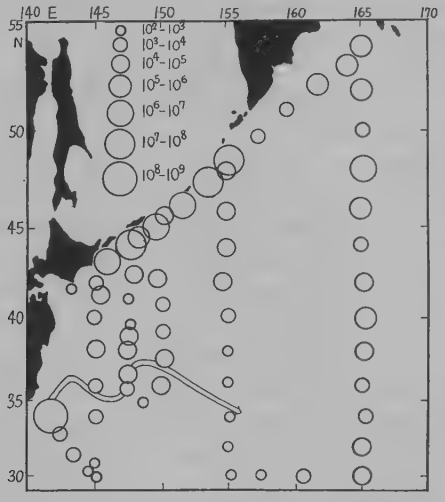

Fig. 4. Distribution of diatom cell numbers per cubic meter in the surface layer.

reaching 240,000,000 per cubic meter and the water is characterized by the prevalence of neritic species.

To express the diatom communities, the following method is used. The percentage to the total diatom cells is calculated for each species at each station, and only the species of more than 10% are illustrated with one to five symbols according to their percentage. Namely, a symbol corresponds to about 10-20%, and when a community is occupied by almost only one species, all of the five symbols are identical. By using such an expression a general view of diatom distributions is easily taken. Thus, the area investigated is divided into seven regions from properties of diatom communities, namely two regions of cold-water communities, four regions of warm-water communities and a region of mixed community, as shown in Fig. 5 and Table 1, although the distinction of their properties are not always possible near the boundaries of the regions.

Thalassiothrix longissima occurs in all areas, but it fluctuates largely in cell number and in percentage. A group of genus *Chaetoceros* is indicative of a watermass influenced by neritic waters. In this genus, subgenus *Hyalochaete* especially shows a very strong tendency to neritic waters, either it belongs

to cold-water species or to warm-water ones. For most of diatom species the distinction of oceanic and neritic features is obvious, while for dinoflagellates it is not always evident.

The property of diatom communities in each region is as follows.

(A) Cold-water communities.

1. P-H (*Phaeoceros-Hyalochaete*) region.

This region is situated like a belt to the south of the Kurile Islands. The diatom community is neritic and is characteristic of cold water. *Chaetoceros atlanticus*, *Chaetoceros concavicornis* and cold water *Hyalochaete* (*Chaetoceros compressus*, *Chaetoceros constrictus*, *Chaetoceros debilis*, *Chaetoceros decipiens*, *Chaetoceros radicans*) are prevalent. And *Nitzschia seriata*, *Rhizosolenia hebetata* f. *hiemalis*, *Rhizosolenia hebetata* f. *semispina* and *Coscinodiscus* spp. also occur. It is a remarkable distribution that warm-water species such as *Chaetoceros lorenzianus* and *Rhizosolenia styliformis* are found around 155°E near the islands though not abundant. This means that the Kuroshio water has extended to such a far north region, overlying the cold water. Details about this will be discussed later. The water of the P-H region is considered to be mainly originated from the Okhotsk water, judging from the diatom community.

2. P-D (*Phaeoceros-Denticula*) region.

This region is situated to the southeast of the Kamchatka Peninsula. The community is characteristic of cold water. *Chaetoceros concavicornis* and *Denticula marina* are predominant, and *Chaetoceros atlanticus*, *Corethron hystrix*, *Nitzschia seriata*, *Rhizosolenia hebetata* f. *semispina*, *Thalassiothrix longissima* and *Coscinodiscus* spp. are also found. This community is distinctly distinguished from the former P-H community in the following two respects, although these are both characteristic of cold water. Namely, *Denticula marina* is abundant in this region, but completely absent in the former region, while subgenus *Hyalochaete* and *Rhizosolenia hebetata* f. *hiemalis* are not found in this region, but present in the former region. A similar distinction is also recognized for copepod communities obtained by the net method in the two regions. An assumption is probably followed that the P-D community is characteristics of the Bering Sea in contrast to the neritic P-H community originating from the Okhotsk Sea.

(B) Warm-water communities.

3. C (*Chaetoceros*) region.

This region extends to 155°E along the Kuroshio main current from the

Table 1. Occurrence of diatoms in each region.

	Species \ Community	Cold-water community		Warm-water community				Mixed
		P-H	P-D	C	C-T	T	He-T	
Cold-water species	*Chaetoceros atlanticus* Cl.	###	##					+
	Chaetoceros concavicornis Mang.	###	###			+		###
	Cold-water *Hyalochaete*(1)	###						+
	Corethron hystrix Hen.		##					+
	Denticula marina Semina		###					
	Rhizosolenia hebetata f. *hiemalis* Gran	##						+
	Rhizosolenia hebetata f. *semispina* Gran	###		+		+		##
Warm-water species	*Chaetoceros coarctatus* Laud.			###	###	##	##	###
	Chaetoceros peruvianus Brightw.			##	##	##	##	###
	Warm-water *Phaeoceros*(2)			##	##	##		
	Chaetoceros lorenzianus Grun.	+		###	###			###
	Warm-water *Hyalochaete*(3)	+		##	##			
	Climacodium frauenfeldianum Grun.			##	##		##	+
	Hemiaulus hauckii Grun.			##	##		###	
	Rhizosolenia styliformis Brightw.	+		##		##	##	
	Warm-water *Rhizosolenia*(4)			##	##	##	###	###
Cosmopolitan species	*Coscinodiscus* spp.	##	##				##	##
	Thalassiothrix longissima Cl. and Grun.	###	###	##	###	###	###	###
	Nitzschia seriata Cl.	##	###	##	##	##	##	

(1) *Chaetoceros compressus* Laud., *Chaetoceros constrictus* Gran, *Chaetoceros debilis* Cl., *Chaetoceros decipiens* Cl., *Chaetoceros radicans* Schütt.

(2) *Chaetoceros atlanticus* v. *neapolitana* (Schröd.) Hust., *Chaetoceros dadayi* Pav., *Chaetoceros tetrastichon* Cl.

(3) *Chaetoceros affinis* Laud., *Chaetoceros curvisetus* Cl., *Chaetoceros didymus* Ehr., *Chaetoceros messanensis* Castr.

(4) *Rhizosolenia alata* Brightw., *Rhizosolenia bergonii* H. Per., *Rhizosolenia calcar avis* M. Schulty, *Rhizosolenia shrubsolei* (Cl.) Schröd.

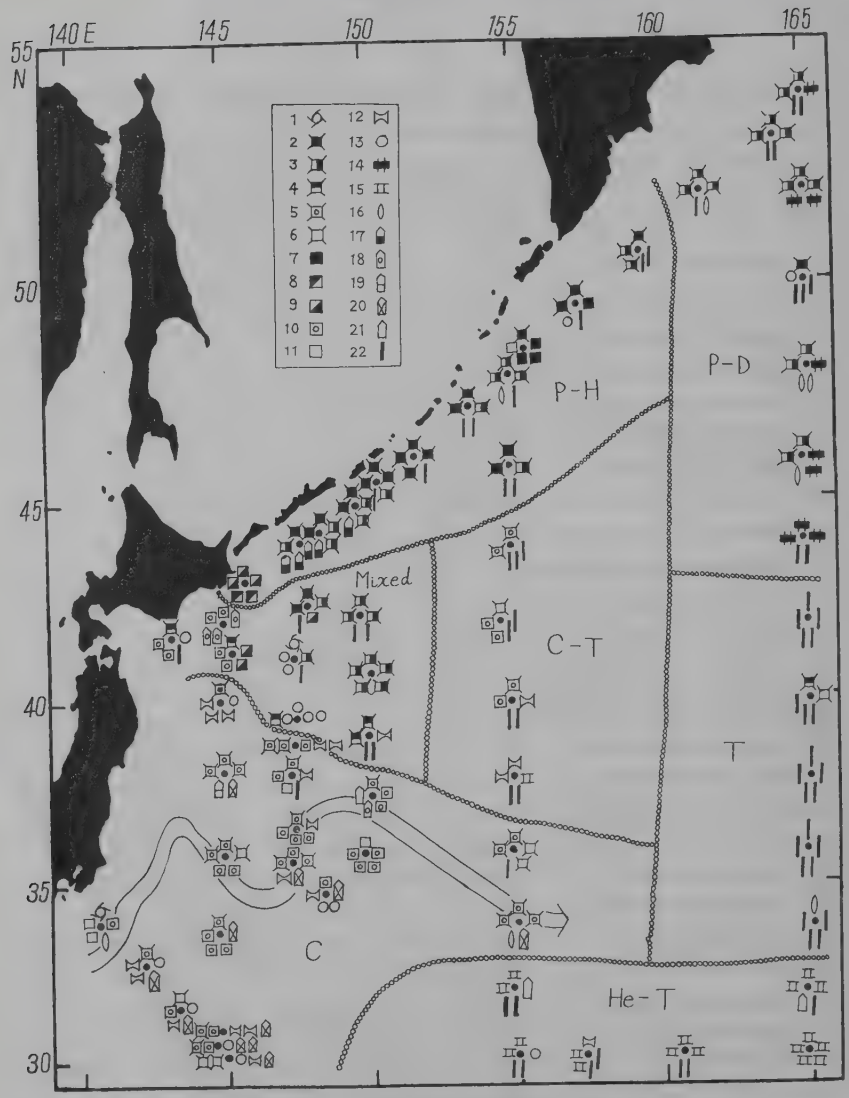

Fig. 5. Distribution of diatom community in the surface layer.
(1) *Bacteriastrum varians*, (2) *Chaetoceros atlanticus*, (3) *C. concavicornis*, (4) *C. peruvianus*, (5) *C. coarctatus*, (6) *C. dadayi*, *C. tetrastichon*, (7) *C. debilis*, (8) *C. compressus*, (9) *C. radicans*, (10) *C. lorenzianus*, (11) *C. affinis*, *C. curvisetus*, *C. didymus*, *C. messanensis*, (12) *Climacodium frauenfeldianum*, (13) *Coscinodiscus* spp., (14) *Denticula marina*, (15) *Hemiaulus hauchii*, (16) *Nitzschia seriata*, (17) *Rhizosolenia hebetata* f. *semispina*, (18) *R. alata*, (19) *R. calcar avis*, (20) *R. styliformis*, (21) *R. bergonii*, *R. shrubsolei*, (22) *Thalassiothrix longissima*.

coastal area near Japan. The community is from the Kuroshio neritic water, because genus *Chaetoceros* prevails and the number of species is large. The principal species are *Chaetoceros coarctatus* and *Chaetoceros lorenzianus*, and *Rhizosolenia styliformis* is next to them. *Climacodium frauenfeldianum* occurs in a fairly high percentage at some stations. The most striking feature in this region is the species number larger than in any other regions, especially largest at station B327 near Japanese coast.

4. C T (*Climacodium-Thalassiothrix*) region.

This region is along the longitude of 155°E between the C- and P-H regions. The species are the same as those found in the C-region, but the prevalence of *Thalassiothrix longissima* is a point distinguishable from the C-community. The diatom community is characteristics of warm water and it is formed by both of neritic and oceanic species, namely many species belonging to genus *Chaetoceros* and *Thalassiothrix longissima*. The following species also occur: *Chaetoceros coarctatus*, *Chaetoceros atlanticus* v. *neapolitana*, *Chaetoceros peruvianus*, *Chaetoceros affinis*, *Chaetoceros didymus*, *Chaetoceros lorenzianus*, *Chaetoceros messanensis*, *Climacodium frauenfeldianum*, *Hemiaulus hauckii*, *Nitzschia seriata*, *Rhizosolenia alata*, *Rhizosolenia bergonii*, *Rhizosolenia calcar avis*, *Rhizosolenia styliformis* and *Rhizosolenia hebetata* f. *semispina*. All of these belong to the Kuroshio species, except *Rhizosolenia hebetata* f. *semispina*.

5. T (*Thalassiothrix*) region.

In this region along 165°E *Thalassiothrix longissima* forms an almost monotonous community. Diatom species identified are not so many, and they are *Chaetoceros atlanticus* v. *neapolitana*, *Chaetoceros coarctatus*, *Chaetoceros peruvianus*, *Chaetoceros concavicornis*, *Rhizosolenia alata*, *Rhizosolenia calcar avis*, *Rhizosolenia styliformis*, *Rhizosolenia hebetata* f. *semispina* and *Rhizosolenia shrubsolei*. The occurrence of *Chaetoceros concavicornis* at the northern stations of this region means that there is more or less an influence of the cold water. One of the most important points is the perfect absence of warm-water *Hyalochaete* which is ubiquitously found in the C- and C-T regions. Consequently this region is considered to be properly oceanic without any neritic features.

6. He-T (*Hemiaulus hauckii-Thalassiothrix*) region.

This region is an offshore part to the south of 33°N. *Hemiaulus hauckii* is most important and *Thalassiothrix longissima* is next to it. *Chaetoceros coarctatus*, *Chaetoceros peruvianus*, *Coscinodiscus* spp., *Climacodium frauen-*

feldianum, *Nitzschia seriata*, *Rhizosolenia calcar avis*, *Rhizosolenia shrubsolei* and *Rhizosolenia styliformis* are also present, but any species of subgenus *Hyalochaete* are not found, as in the T region. This diatom community is a pure oceanic Kuroshio one which is not affected by cold waters at all. According to the author's unpublished data, a diatom community with the prevalence of *Hemiaulus hauckii* is widely distributed around 20°N in the open Pacific Ocean, indicating the oceanic character.

(C) 7. Mixed region.

This region is situated between the C- and P-H regions. The Oyashio and Kuroshio species occur in various ways of mixing at the stations, and therefore the features are not so easily generalized. Many species were identified in this region.

Distributional boundaries of principal diatom species are shown in Fig. 6.

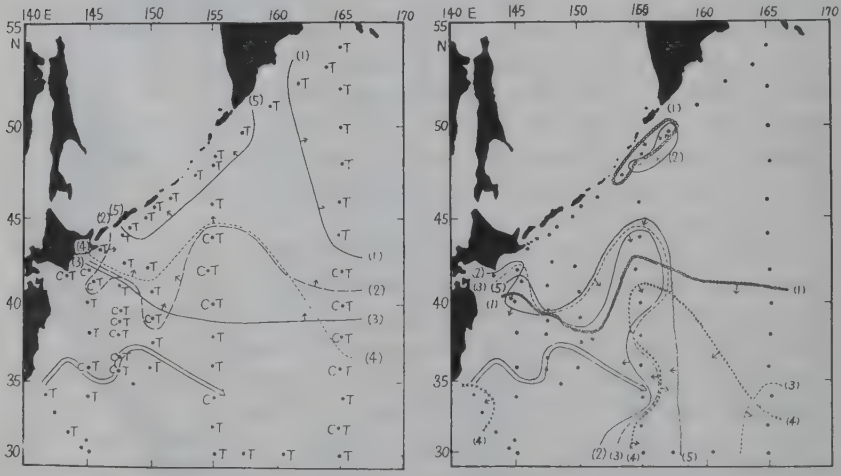

Fig. 6. Left: Southern boundary lines of cold-water diatoms and occurrence of *Chaetoceros peruvianus* (C) and *Thalassiothrix longissima* (T). (1) *Denticula marina*, (2) *Chaetoceros concavicornis*, (3) *Rhizosolenia hebetata* f. *semispina*, (4) *Chaetoceros atlanticus*, (5) *C. debilis*.

Right: Northern boundary lines of warm-water diatoms. (1) *Rhizosolenia styliformis*, (2) *Chaetoceros lorenzianus*, (3) *C. coarctatus*, (4) *Hemiaulus hauckii*, (5) *Climacodium frauenfeldianum*.

Species belonging to the cold-water *Hyalochaete* are restricted within the area around the Kurile Islands, indicating an extent of neritic influence. In the Kuroshio area, neritic species such as *Hyalochaete* species are restricted to the west of 155°E and perfectly disappear at the latitude of 165°E where oceanic species prevail. Along 155°E such warm-water species as *Rhizosolenia styliformis*, *Chaetoceros lorenzianus* and *Ceratium inflexum* (a dinoflagellate) extend far northwards and are found even around the northeastern part of the Kurile Islands. This distribution seems to show that the southern Kuroshio water has gone thereto over the underlying cold water. However, any similar phenomenon is not observed for the copepod distribution in the upper 150-m layer, as will be mentioned later.

(2) Dinoflagellates.

By the filtering method dinoflagellates can be caught fairly abundantly. Any characteristic difference is not found between the cell numbers of cold- and warm-water dinoflagellates. The population does not especially increase, neither in the northern Oyashio area nor in the coastal area (Fig. 7). The cell number is in general several hundreds to several thousands per cubic meter, with exception of over 10,000 at five stations and absence at two stations. Each of the species has its peculiar distribution, but they can be roughly classified into the follcwing two groups.

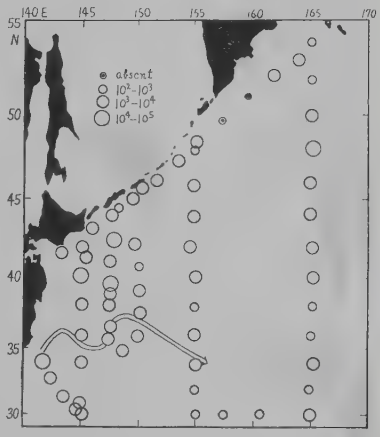

Fig. 7. Distribution of dinoflagellate cell numbers per cubic meter in the surface layer.

Cold-water species:

Ceratium arcticum (Ehr.) Cl.
C. longipes (Bail.) Gran
C. fusus (Ehr.) Dujar.
C. tripos (O.F. Müller) Nitz.
C. macroceros subsp. *gallicum* (Ehr.)
C. kofoidii Jörg.

Warm-water species

Ceratium inflexum (Gour.) Kof.
C. karsteni Pavil.

C. trichoceros (Ehr.) Kof.
C. deflexum (Kof.) Jörg.
C. massiliense (Gour.) Jörg.
C. extensum (Gour.) Cl.
C. contortum Cl.
C. candelabrum (Ehr.) Stein
C. carriense Gour.
C. furca (Ehr.) Dujar.
C. humile Jörg.
C. pulchellum Schör.
C. reticulatum (Poch.) Cl.
C. sumatranum Jörg.
C. sumatranum f. *angulatum* Jörg.
C. pennatum Kof.
C. tenue Ost. and Schm.
Pyrocystis pseudonoctiluca Mur.
P. fusiformis Mur.
Pyrophacus holorogicum Stein

In dinoflagellates the distinction between oceanic and neritic species is not generally recognized and the distributional boundary lines are parallel to the latitude in many species, while most of diatom species show either oceanic or neritic feature (Fig. 8). Among principal warm-water species, *Ceratium in-*

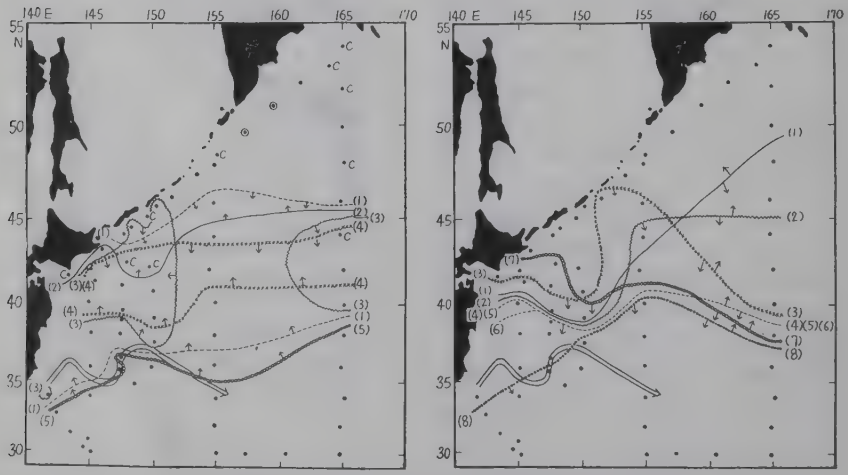

Fig. 8. Left: Southern boundary lines of cold-water dinoflagellates. (1) ***Ceratium macroceros*** subsp. ***gallicum***, (2) ***C. arcticum***, (3) ***C. tripos***, (4) ***Dinophysis homunculus*** v. ***tripos***, (5) ***Ceratium tripos***.
Right: Northern boundary lines of warm-water dinoflagellates. (1) ***Pyrocystis pseudonoctiluca***, (2) ***Ceratium trichoceros*** (3) ***C. inflexum***, (4) ***C. deflexum***, (5) ***C. massiliense***, (6) ***C. extensum***, (7) ***Pyrophacus horologicum***, (8) ***Ceratium contortum***.

flexum, *Ceratium trichoceros* and *Pyrocystis pseudonoctiluca* extend exceedingly northwards, and *Ceratium deflexum*, *Ceratium massiliense* and *Certium extensum* are restricted within the area more southern than the former dinoflagellates.

Among cold-water dinoflagellates, *Ceratium arcticum*, and *Ceratium longipes* are most typical and the former streches more southwards than the latter. *Ceratium fusus* is distributed in the Oyashio and transition areas, but not in the Kuroshio area south of the main current in our survey. According to Kokubo (1940), however, it is ubiquitous in Japanese coasts, being found also in Sakhalin and Formosa coasts. Thus the geographical distribution of one species in open seas seems to be different from that in coastal seas in some case. *Ceratium tripos* occurs approximately in the transition area west of 150°E, while *Ceratium macroceros* subsp. *gallicum* is restricted within the area east of 155°E. *Ceratium kofoidii* occurs only at stations B464, 1040 and 1041 of the Oyashio water. The dinoflagellate community is noticeable at two stations of the Kuroshio water. Namely, at station B327 *Ceratium fusus*, *Ceratium macroceros* subsp. *gallicum* and *Ceratium tripos* occupy 16% of total dinoflagellates and at station B335 *Ceratium tripos* occupies 19% and such a community differs distinctly from that of the oceanic Kuroshio.

(3) Other microplankton.

Cold-water tintinnods, *Parafavella* spp., *Ptycocylis obtusa* Bran. and *Acanthostomella norvegica* (Dad.) Jörg. are found (Fig. 9). *Parafavella* spp. are distributed in the sea north of the Oyashio front and *Ptycocylis obtusa* is restricted within the far northern area. *Rhabdonella spiralis* (Fol.) Bran., *Xystonella treforti* (Dad.) Laac. and *Cyttarocylis brandti* Kof. and Cam. occur in the Kuroshio water.

Blue-green algae, *Trichodesmium thiebauti* Gom., *Katagnymene spiralis* Lem. and *Katagnymene pelagica* Lem. occur in the Kuroshio southern area.

Such neritic forms, as *Evadne tergestina* Claus, *Penilia schmackeri* Rich. (Cladocera), *Noctiluca scintillans* Macar., ophiopluteus, cirriped cypri-form larvae and pelecypod larvae (larvae of littoral benthic animals) are only found in the sea west of 150°E and this distribution is considered to indicate the extension of coastal water thereto.

Remains of 15,000 ophiopluteus and some quantity of pelecypod larvae were collected at station B458 near the tip of the Kamchatka Peninsula. Their oc-

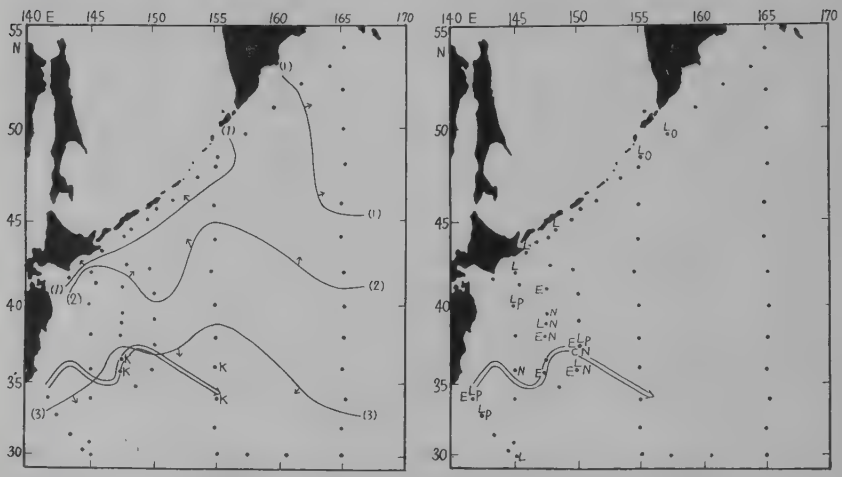

Fig. 9. Left: Southern boundary lines of *Ptycocylis obtusa* (1) and *Parafavella* spp. (2), northerm boundary line of *Trichodesmium thiebauti* (3), and occurrence of *Katagnymene spiralis* and *K. pelagica* (K).
Right: Occurrence of *Evadne tergestina* (E), *Penilia schmackeri* (P), *Noctiluca scintilans* (N), pellecypod larvae (L), cirripedia cypriform larvae (C) and ophiopluteus larvae (O).

currence shows an arrival of the northern coastal water to the station, in accord with JOHNSON's report (1953) that ophiopluteus larvae are very abundant in the coastal area of Bering Sea.

5. A diatom, Chaetoceros radicans Schütt, collected by the centrifugal method.

The authors have encountered with peculiar distributions of a minute diatom, *Chaetoceros radicans* Schütt, which is densely populated in restricted areas and restricted layers in warmer seasons. Also in this investigation a similar interesting result was obtained, as is illustrated in Fig. 10. This is a typical neritic diatom in the seas around Japan. In the surface layer it is found mainly in the coastal Oyashio water near Hokkaido in this investigation, while it becomes to occur at the 20-m, 50-m and 100-m depths to the south of Hokkaido and in the eastern offshore areas, and to occur only in the 50-m depth in 155°E. The distribution of this diatom is restricted to the transition area with the

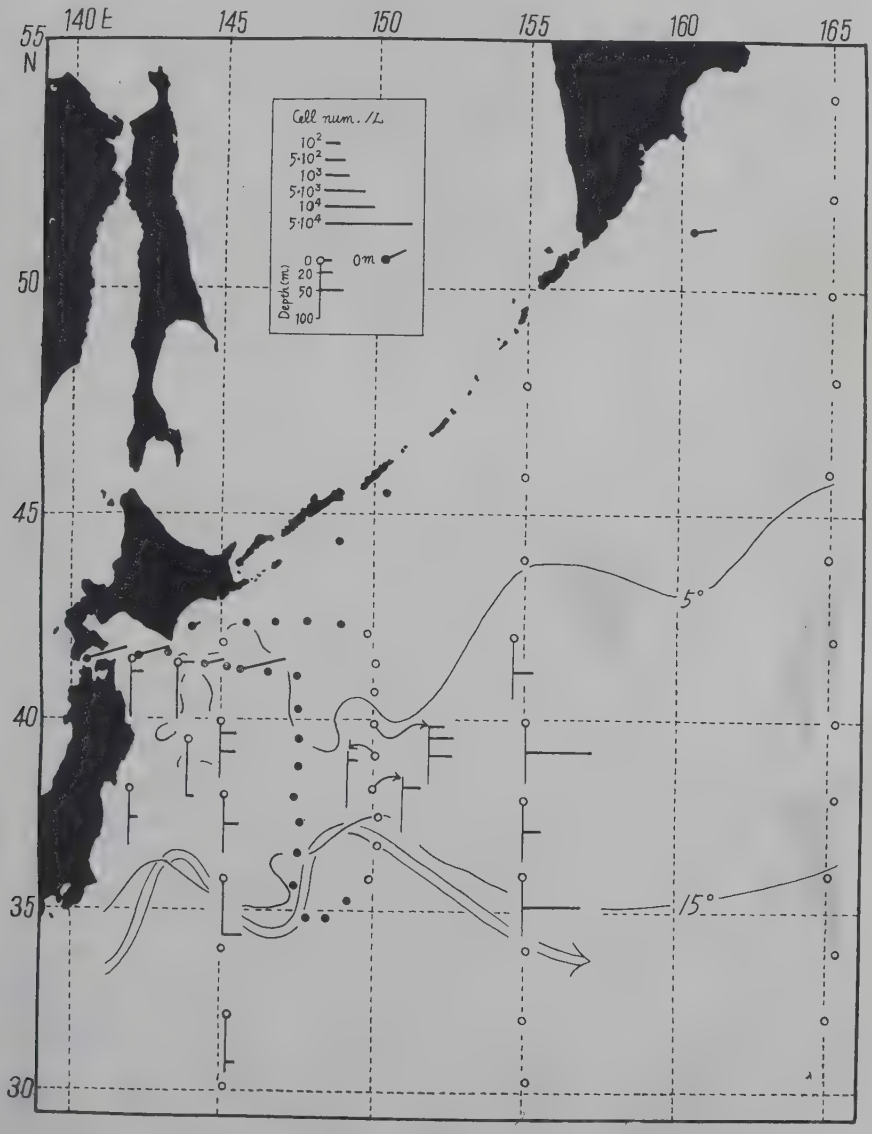

Fig. 10. Distribution of *Chaetoceros radicans* and 100-m isotherms. ● denotes surface observational stations, and ○ serial observational stations.

exception of station 1004 in the Kuroshio water and station B 461 near the Kamchatka Peninsula, and this species is perfectly absent along 165°E.

The following conclusion would be probably drawn from the distribution. *Chaetoceros radicans*, originating from the surface Oyashio water near Hokkaido, is submerged to lower layers in southern and eastern parts of the transition area, because of the Oyashio water overlaid by the Kuroshio water there, but it still continues to propagate. However, it disappears perfectly along 165°E, probably because the water is too oceanic for the survival of this neritic diatom. It is a very interesting distribution that *Chaetoceros radicans* is found almost only in the transition area. The Kuroshio main current seems to form a strong barrier preventing the southern extension of this species across the current.

6. Copepods collected by the net method.

One hundred twenty-nine species of copepod were identified from the materials collected with the Norpac Plankton Net. The species number is generally large in the southern area, decreasing northwards (Fig. 11). The species number of cold-water type is large in the area north of 10°C isotherm at the 100-m depth. The species number of warm-water type is largest in the Kuroshio area, and it suddenly decreases northwards across the Kuroshio front. Among 129 species, 43 are important, being found with a high frequency of occurrence in restricted sea areas, and so explanation is mainly made about them in relation to the oceanographic conditions. Copepods are classified into four groups by their distributional patterns. Species beloging to each group and their frequency

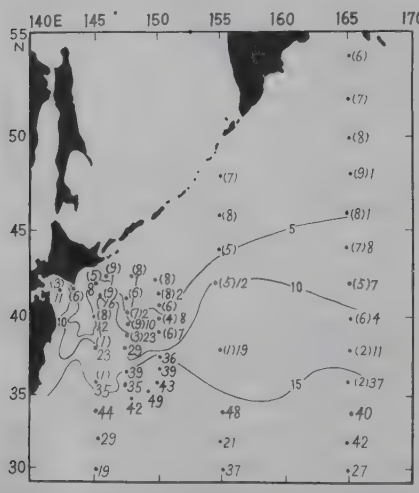

Fig. 11. Distributions of the species number of warm-water copepods (numerals without brackets) and cold-water copepods (numerals in brackets) in the upper 150-m layer and the 100-m isotherms.

of occurrence are shown in Table 2, and the distributions of representative species in each group are shown in Fig. 12. In the present study any cosmo-

Table 2. Frequency of occurrence of principal copepods in the upper 150-m layer. Figures denote the number of stations where the copepods were present.

Sea area Water temperature at the 100-m depth Number of stations	Oyashio area <5° C 16	Transition area 5°-15° C 16	Kuroshio area >15° C 17
Calanus cristatus Kröyer	13	5	—
Cal. plumchrus Marukawa	16	10	—
Eucalanus bungii bungii Johnson	16	9	—
Pseudocalanus minutus (Kröyer)	16	8	—
Metridia lucens Boeck	16	13	1
Oithona similis Claus	16	12	1
Paracalanus parvus Giesbrecht	6	14	6
Centropages bradyi Wheeler	1	8	3
Calanus tenuicornis (Dana)	2	11	10
Clausocalanus arcuicornis (Dana)	1	11	17
Clausocalanus pergens Farran	—	7	12
Ctenocalanus vanus Giesbrecht	2	10	11
Oithona plumifera Baird	6	16	16
Calanus darwinii (Lubbock)	—	1	14
Cal. gracilis (Dana)	—	2	10
Cal. minor (Claus)	—	5	17
Cal. pauper Giesbrecht	—	—	8
Eucalanus attenuatus (Dana)	—	3	12
E. pileatus Giesbrecht	—	4	10
E. subtenuis Giesbrecht	—	3	14
Mecynocera clausi Thompson	—	2	13
Paracalanus aculeatus Giesbrecht	—	1	8
Calocalanus pavo (Dana)	—	2	12
Calocal. plumulosus (Claus)	—	2	11
Clausocalanus furcatus (Brady)	—	2	11
Aetideus giesbrechti Cleve	—	1	8
Euchaeta longicornis Giesbrecht	—	—	9
Euch. marina Prestandrea	—	—	9
Scolecithrix danae (Lubbock)	—	3	12
Temora discaudata Giesbrecht	—	3	10
Pleuromamma gracilis (Claus)	—	3	10
Lucicutia flavicornis (Claus)	—	3	14
Heterorhabdus papilliger (Claus)	—	4	11
Haloptilus longicornis (Claus)	—	—	9
Candacia aethiopica Dana	—	—	8
Cand. truncata (Dana)	—	—	8
Acartia negligens Dana	—	4	11
Oncaea media Giesbrecht	—	7	14
Onc. venusta Philippi	—	6	16
Sapphirina spp.	1	8	12
Corycaeus spp.	1	6	15
Copilia spp.	—	4	11

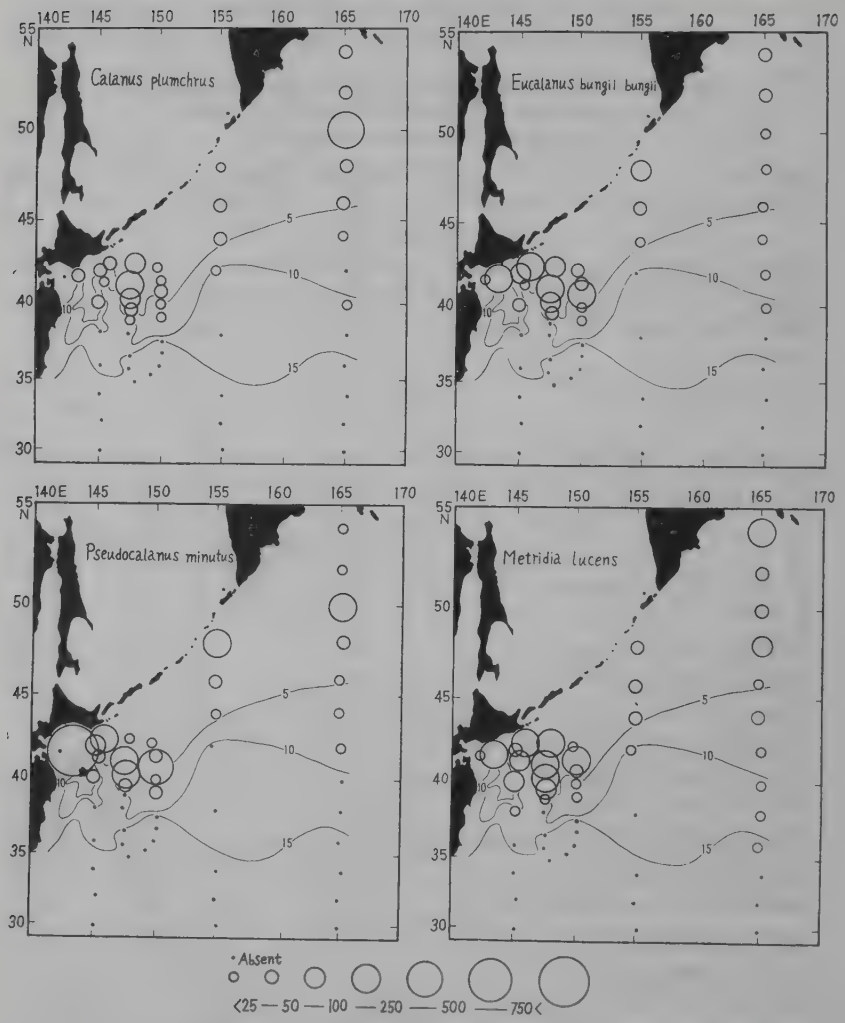

Fig. 12-1. Distributions of the individual number of *Calanus plumchrus*, *Eucalanus bungii bungii*, *Pseudocalanus minutus* and *Metridia lucens* per cubic meter in the upper 150-m layer and the 100-m isotherms.

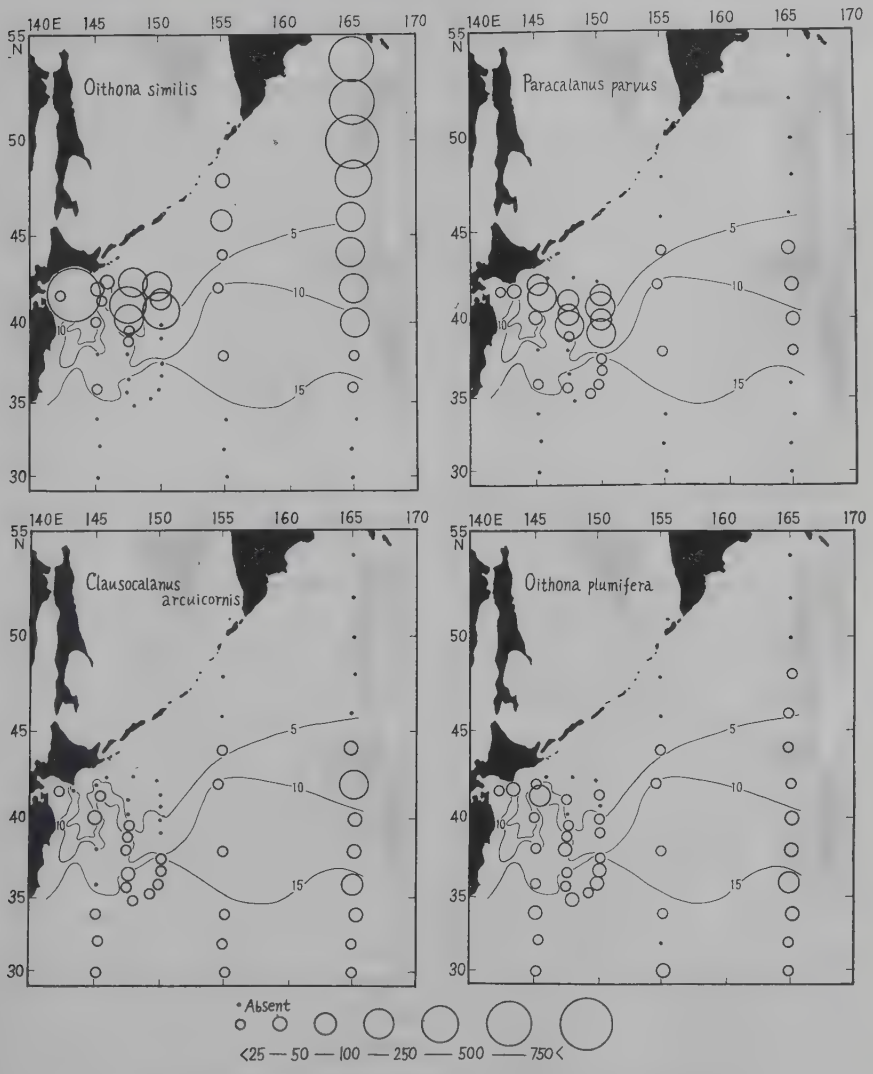

Fig. 12-2. Distributions of the individual number of *Oithona similis*, *Paracalanus parvus*, *Clausocalanus arcuicornis* and *Oithona plumifera* per cubic meter in the upper 150-m layer and the 100-m isotherms.

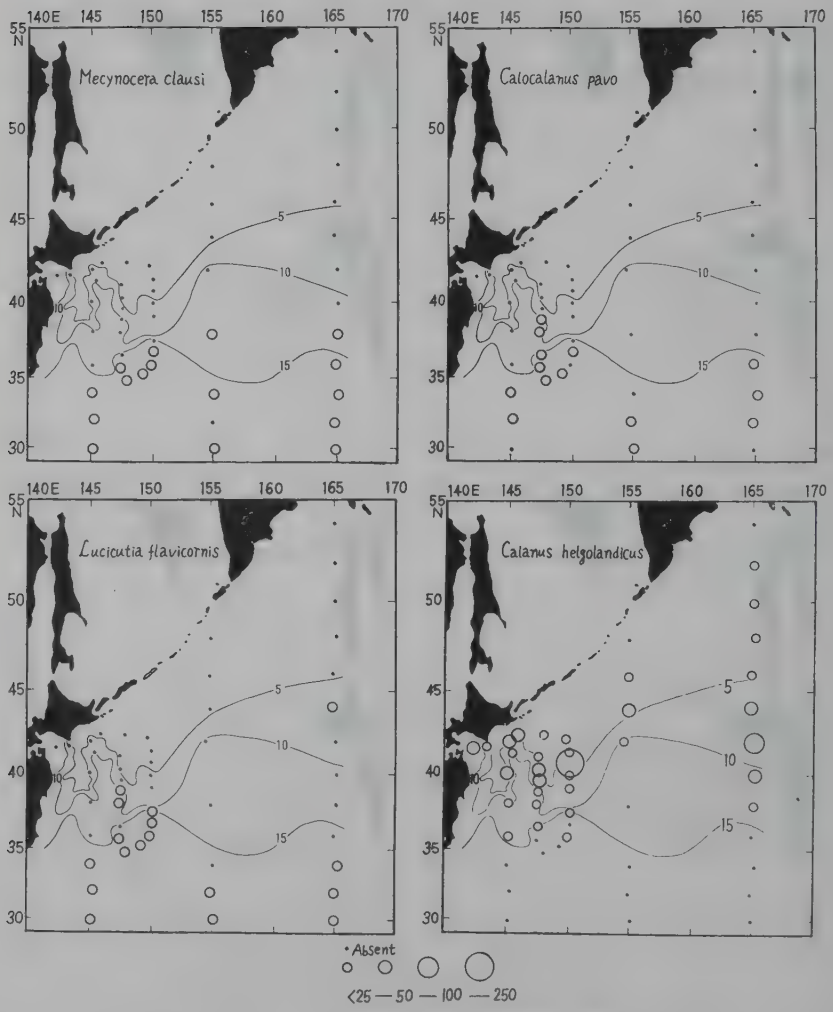

Fig. 12-3. Distributions of the individual number of *Mecynocera clausi*, *Calocalanus pavo*, *Lucicutia flavicornis* and *Calanus helgolandicus* per cubic meter in the upper 150-m layer and the 100-m isotherms.

politan species inhabiting ubiquitously in the whole area from the Oyashio to the Kuroshio is not found.

(1) A-group.

Copepods of this group are reported to be cold-water species and to occur with the highest frequency in the Oyashio area. *Oithona similis*, *Metridia lucens*, *Eucalanus bungii bungii*, *Pseudocalanus minutus* and *Calanus plumchrus* are the principal constituents of this group. *Pareuchaeta japonica*, *Racovitzanus antarcticus*, *Scolecithricella minor* and *Candacia columbiae* are also typical cold-water species, though they are uncommon and occur only in a small number. Copepods of this group are generally distributed in the sea north of 10°C isotherm at the 100-m depth, but only two species, *Oithona similis* and *Metridia lucens*, occur also in the area south of 10°C isotherm.

(2) B-group.

This group contains copepods which are mainly distributed in the transition area. A representative species is *Paracalanus parvus*, which has been commonly regarded as a neritic warm-water copepod.

(3) C-group.

Species of this group are widely distributed in both of the transition and the Kuroshio areas. They have been considered as warm-water types. *Clausocalanus arcuicornis*, *Ctenocalanus vanus* and *Oithona plumifera* are numerous.

(4) D-group.

Species of this group have typical warm-water characteristics and occur mainly in the Kuroshio area, but to some extent also in the transition area. Main small copepods of this group are *Mecynocera clausi*, *Paracalanus aculeatus*, *Calocalanus pavo*, *Calocalanus plumulosus*, *Clausocalanus furcatus*, *Lucicutia flavicornis*, *Acartia negligens*, *Corycaeus concinnus* and *Corycaeus flaccus*. Main large copepods are *Calanus darwinii*, *Calanus gracilis*, *Calanus minor*, *Calanus pauper*, *Eucalanus attenuatus*, *Aetideus giesbrechti*, *Euchaeta marina*, *Euchaeta longicornis*, *Scolecithrix danae*, *Temora discaudata*, *Candacia aethiopica*, *Candacia truncata*, *Sapphirina* spp. and *Copilia* spp. Typical warm-water species, *Calanus robustior*, *Calanus vulgaris*, *Acrocalanus gibber*, *Acrocalanus gracilis*, *Acrocalanus monachus* and *Euchaeta wolfendeni*, are entirely confined within the Kuroshio area, occurring not so frequently as the above-mentioned copepods of this group.

(5) Distribution of *Calanus helgolandicus (Claus)*.

Here, some consideration is to be made about the distribution of *Calanus helgolandicus* (Fig. 12). It has been mentioned by many research workers that this species has two size groups. Specimens obtained in the present collection belong to the smaller size group with a protruded head, being less than 2.5 mm in body length. Therefore, these specimens are considered to be indentified as *Calanus finmarchicus* v. *helgolandicus* proposed by TANAKA (1956). *Calanus helgolandicus* occurs very frequently in the Oyshio and transition areas like *Oithona similis* and *Metridia lucens*. However, this species is not considered to be indicative of the Oyashio water, because it occupies a higher percentage at several stations in the transition area than in the Oyashio area, and also it is one of the most important constituents of copepod commuities in the Tsugaru warm-water area. According to KIMURA and ODATE (1957), *Calanus helgolandicus* is not indicative of the Oyashio water.

Table 3. Mean Composition of copepod communities in each area in the upper 150-m layer.

Sea area	Oyashio area		Transition area	Kuroshio area
	West of 155°E	165°E		
	%	%	%	%
Calanus plumchrus	10	11	2	—
Eucalanus bungii bungii	15	2	3	—
Pseudocalanus minutus	19	4	5	—
Metridia lucens	16	8	9	0
Oithona similis	26	71	11	0
Calanus helgolandicus	5	1	5	0
Paracalanus parvus	6	—	16	1
Clausocalanus arcuicornis	0	—	7	9
Clausocal. pergens	—	—	3	3
Ctenocalanus vanus	0	—	3	1
Oithona plumifera	1	0	11	12
Paracalanus aculeatus	—	—	0	2
Calocalanus pavo	—	—	0	2
Clausocalanus furcatus	—	—	0	5
Lucicutia flavicornis	—	—	0	3
Acartia negligens	—	—	1	2
Oncaea media	—	—	2	6
Onc. venusta	—	—	3	11
Corycaeus concinnus	—	—	0	3
Cory. flaccus	—	—	0	2
Others	0	3	12	23
juv. not identified	2	1	8	17

(6) Copepod communities.

a. In the Oyashio area (north of the Oyashio front), *Oithona similis*, *Metridia lucens*, *Pseudocalanus minutus*, *Eucalanus bungii bungii* and *Calanus plumchrus* are the most important constituents and they occupy about 90% of total copepods. The leading species are, however, different in the following two regions, as shown in Table 3. Namely, in the area west of 155°E all of the five species mentioned above are prevailing with their percentages fluctuating fairly widely at each station, while in the region along 165°E *Oithona similis* is so predominant as to make a monotonous community.

b. In the Kuroshio area (south of the Kuroshio front) a large number of species are found, each species having a small percentage, and there exists no prevalent species such as *Oithona similis* in the Oyashio area. Large-sized copepods are abundant in species number, but have small percentages, less than 7%, in this area. Total percentage of warm-water species generally reaches about 80-90% in the Kuroshio area.

c. In the transition area, going southwards across the Oyashio front, the total perecentage of cold-water species rapidly decreases to 50%, and then it gradually decreases southwards in the transition area. The total percentage of warm water species decreases northwards from the Kuroshio front, although at stations 1029 and 1056 it shows high amounts as it does in the Kuroshio area. Thus, copepod communities with the prevalence of the Oyashio species occur in the area north of 10°C isotherm, and those with prevalence of the Kuroshio species occur south of the isotherm. The transition area is characterized by an abundant occurrence of *Paracalanus parvus*. This species prevails especially along the southern side of the Oyashio front west of 155°E, and has 30–50% there.

(7) Number of copepods and the wet weight of zooplankton.

A large population of copepods over 500 individuals per cubic meter is seen along the Oyshio front west of 150°E, as shown in Fig. 13. However, the population is not so dense in the Oyashio area along 155°E. In the Kuroshio and transition areas, it is generally thin, less than 250 individuals, though it is comparatively large in 165°E. The smallest number less than 50 is obtained from stations 1003, 1007 and 1053.

The wet weight of zooplankton shows a distribution almost similar to that

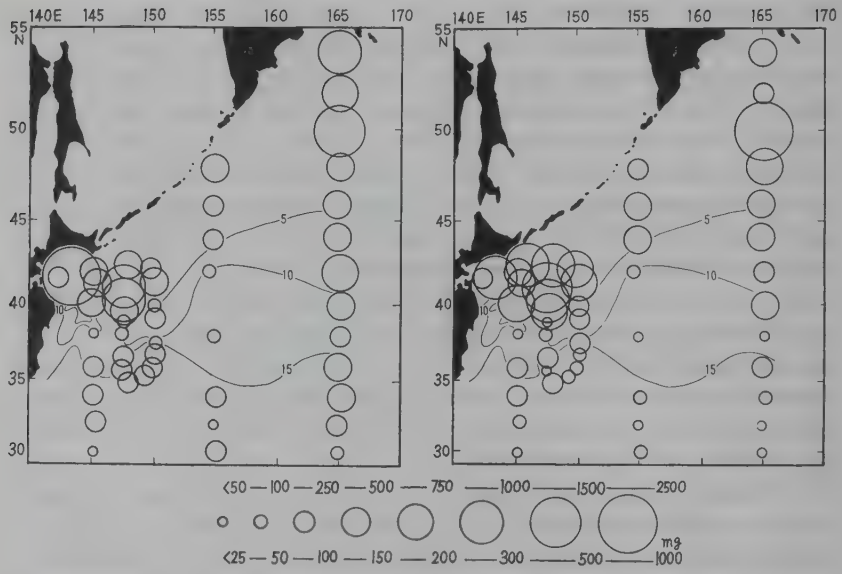

Fig. 13. Distributions of the individual number of copepods (left), the total zooplankton wet weight (right) per cubic meter in the upper 150-m layer, and the 100-m isotherms.

of copepods, and is fairly large in the Oyashio area, decreasing gradually southwards from the Oyashio front. And this depends not only upon the abundance of copepods but also upon that of chaetognaths such as *Sagitta elegnas* (Verrill) and *Eukrohnia hamata* (Möbius).

7. Discussions.

(1) Microplankton in the surface layer.

In the said sea area there exist three types of watermasses, namely the northern cold Oyashio water orginating from the Okhotsk and Bering seas, the southern warm water of the Kuroshio and the water of the transition area between these cold and warm waters. In accordance with watermasses, features of the plankton community also fluctuate from the Oyashio features to the Kuroshio features. A peculiar surface water system develops in this area in summer because of the violent meteorological influence, and it seems to be

more clearly analysed by plankton than by hydrographical elements such as water temperature and chlorinity which are easily changed in the surface layer in summer.

Many warm-water diatoms extend to the north of 47°N along 155°E in the surface water, and especially *Ceratium inflexum* occurs even at a northern station B452 with 4.2°C. It is probable inferable that the surface Kuroshio water reached thereover the underlying Oyashio water. However, such distributions have been already known. For instance, according to Aikawa (1936), a warm-water blue-green alga, *Trichodesmium* is found even at 50°N, 180°E near the Aleutian Islands in summer, and according to Iizuka and Tamura (1958), the northern boundary of subtropical plankton is situated between 40 and 45°N in the western part of the North Pacific Ocean in summer.

In the surface water along 165°E, a typical cold-water diatom, *Chaetoceros atlanticus*, is found at station 1047 with 25.1°C, and *Chaetoceros concavicornis* occurs also in the fairly southern water, while a warm-water dinoflagellate, *Pyrocystis pseudonoctiluca*, is found at a northern station 1042 with 15.3°C. Moreover, distributional boundary lines of diatoms and dinoflagellates are generally scattered along 165°E. The existence of the Kuroshio main current becomes obscure in this longitude and may eddies and counter currents seem to be formed in the transition area along 165°E, as was previously mentioned for the same area by Uda (1935), while it is obviously recognized in the area west of 155°E. Such complexity of the plankton distribution is not observed for copepods in the upper 150-m net samples in the present survey. Thus the plankton distributins in the surface layer above the 20-30 meter depths differ remarkably from those of the lower layers in summer.

Genus *Chaetoceros* is an effective indicator of the Kuroshio neritic water and is distributed near Japanese coasts and in the area around the Kuroshio main current, but perfectly disappears along 165°E. The extension of neritic water is searched also by the occurrence of some cladoceran species and pelagic larvae of littoral benthic animals whose distributions are restricted to the area west of 155°E. Thus, the larger the eastward current speed is, the more faraway these larvae spawned in coastal seas seem to be transported without sinking to lower layers. The conspicuous Oyashio neritic water is seen in the southern area along the Kurile Islands, indicated by cold-water *Hyalochaete*.

(2) Copepods in the upper 150-m layer.

According to ANRAKU (1954), in the western North Pacific warm-water copepods are relatively abundant in species number and scarce in individual number, on the contrary, cold-water copepods are scarce in species and abundant in individual. According to BOGOROV (1958), in the same area as that of the present investigation the plankton biomass near the Kurile Islands is large, but the largest quantity is found rather southwards offshore. And these distributions are almost in accordance with the present results of copepod number and total wet weight in the upper 150-m layer. However, the surface diatom population collected by the filtering method is especially large in the neritic water along the Kurile Islands and gradually decreases southwards. A similar distribution is reported for the phytoplankton biomass in the western part of the North Pacific in the summer and autumn of 1955, according to СЕМИНА (1956).

The Kuroshio front forms the northern boundary of typical warm-water species and the southern boundary of *Oithona similis* and *Metridia lucens* whose distribution extends to the utmost south among cold-water species. The Oyashio front forms the southern boundary of communities with prevalence of cold-water species and the northern boundary of warm-water species.

In the transition area, cold-water and warm-water species intermingle each other. The former is important on the north of 10°C isotherm at the 100 m depth and the latter is important to the south. The transition area is also characterized by the occurrence of *Paracalanus parvus*. This fact is considered to indicate that the influence of coastal warm water prevails there. According to HONJO (1957), the area affected by coastal waters is indicated by the occurrence of *Paracalanus parvus* and *Calanus finmarchicus* in the sea south of Japan. HONJO's *Calanus finmarchicus* may be identical with *Calanus helgolandicus* identified by the authors.

According to TSURUTA and CHIBA (1954) and MINODA (1958), *Oithona similis* is predominant off the eastern coast of Kamchatka. Also, JOHNSON (1953) has stated that this species must be considered as a very important constituent of the surface plankton for the whole Bering Sea in summer. In the present survey this species is abundant in the northern part along 165°E and diminishes gradually southwards. This seems to show that the northern part along 165°E is more or less influenced by the Bering water and a similar distribution is

also seen in the surface diatom community collected by the filtering method.

8. Summary

A plankton study was made in the western area of the North Pacific Ocean with reference to hydrographical conditions. The plankton collection was done by three ways, namely by the filtering, centrifugal and net methods.

(1) Communities of diatoms, dinoflagellates and other microplankton organisms obtained by the filtering method are explained, referring to hydrography of the surface water system which shows complicated properties under the violent meteorological influence during the summer season.

(2) Discussion is made about the characteristic distribution of a diatom, *Chaetoceros radicans* collected from the 0-m, 20-m, 50-m and 100-m depths by the centrifugal method.

(3) Copepods of 129 species were collected in the upper 150-m layer by the net method, and they were classified into four groups according to their distributional patterns. In many species the distributional area is mainly resticted by the Oyashio or Kuroshio front which almost agree with the behaviours of 5 and 15°C isotherms at the 100-m depths respectively.

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Notes on the Hysteresis of BT-Records

By

Masashi YASUI and Tsutomu SAWARA

Japan Meteorological Agency

1. Introduction

Because of its relatively easy observation and of its comparative con servative property sea water temperature is still an important observational element in the modern oceanography. In fact, it is no exaggeration to say that water temperature may always be most useful indicator when we will figure the characters of oceanographic features.

In the past, reversing thermometers and Nansen bottles have been the principal tools for temperature observation. But, since BT (bathythermograph) was designed, these tools are being replaced with BT for measuring temperature in upper layers because of the following three reasons :—(1) Handling of the instrument is very easy, (2) continuous record of vertical distribution of temperature is possible, (3) sub-surface water temperatures can be measured from a vessel underway. Nowadays, the BT is used not only on board the marine research vessel but even on board the fishing boat. Tremendous amounts of BT data contribute to the investigation of thermal structure in the troposphere of the ocean.

Although handling is easy, it seems to us that a little technique is needed to read the temperature from BT-records on slides, that is, there is a problem of hysteresis. When we use BT in the sea which has comparatively large vertical gradient of temperature, the hysteresis is always recognized on records. Now every oceanographer make a correction on reading temperature according to his own empirical knowledge individually. Of course, we have been never worried to analyse these individually corrected data, but it may be desirable to unify or standardize the method of reading temperature from the record with hysteresis in order to make discussion on the fine thermal structure of the subsurface layers.

This paper aims to study the cause of the hysteresis. A suggestion to the temperature reading, which are derived on the basis of several hypothesis, is also given.

2. *A few comments on the hysteresis*

Considering the hysteresis on BT-records, we can easily mention several cause for it. When we use BT from the not-anchored vessel, the actual location of ship is slowly shifted within even in the short period while BT is being submerged and heaved. Then it is plausible that thermal structure changes while the BT is being submerged. In this case, of course the hysteresis will be recognized apparently, but in practice, even when we drop BT successively in a short period from the vessel underway, records show almost same features and difference of each mean distribution on successive two records are usually smaller than breadths of the hysteresis. Then in usual case, it is supposed that the local variations of temperature in the period of observations are so small that it can not be a principal cause of the hysteresis of BT.

When the surface temperature is not same as that of atmosphere, scratches, lengths of which are proportional to the temperature difference, are recorded on BT slides in the situation corresponding to the sea surface. This mark is twice scratched when BT is dropped into water and is heaved out, but we can usually recognize these scratches as one curve. Of course sometimes we can recognize these as the two clearly separated curves, but according to our experiences this separation of two curves may generally be caused rather by a mishap of BT than a special case of normal action. On the other side, differences in the equal-temperature parts on two curves of hysteresis are sometimes 20 meters more over in normal action of BT. Considering these facts and slowness of movement in pressure sensitive device, we may omitt the mechanical friction on the system connected with bellows from the list of phenomena, with which hysteresis of BT will be affected.

Now we examine BT records observed from ships at rest. We can adopt two ways in methods of heaving; in the first case we begin to heave as soon as we have veered away BT-wire to the predetermined length, and in the other case we begin to heave after a few minutes leaving in the state BT-wire has been veered at the predetermined length. In the former case, the smaller the distance from the end point is, the narrower the bredth of hysteresis, and

two curves, recorded in periods of dropping and heaving, are converged in a single curve in neighbourhood of the end point. But in the latter, two curves are clearly separated and in the deepest part the scratch, connecting end points of two curves, is marked in the direction along temperature abscissa.

It seems to us that the magnitude or the scale of hysteresis on records which are obtained in the same location with the same BT is not the same if the speed of sinking and heaving is different. And even if these speeds are regurated in the same conditions, different types of hysteresis are obtained coresponding to different instrument number of BT. And besides quantitative discussions, it seems that the magnitude of hysteresis may have some relation with the length of capillary tube in the thermal sensitive apparatus.

From the above stated considerations, the authors reach a conclusion that we make no large mistake in saying the principal cause of hysteresis on BT-records is the lag of response in the thermal sensitive apparatus.

3. *Mathematical treatment*

Because of the mechanical complexity, it seems impossible to represent the action of BT sufficiently in the mathematical formulae, so we restrict our discussion within the thermal time lag based on the consideration given in previous sections.

Now we denote the vertual water temperature as Θ and the apparent temperature recorded on BT-slides as θ. Assuming there is no resistive influences on the mechanical action in thermal sensitive apparatus, we may obtain the following differential equation from the theory of heat transmission;

$$-\frac{d\theta}{dt}=\mu(\Theta-\theta), \tag{1}$$

where $\frac{1}{\mu}$ is a numerical number which has the same dimension of the thermal time constant of ordinary thermometer.

The integration of this equation gives

$$\theta=Ce^{-\mu t}+\mu e^{-\mu t}\int e^{\mu t}\Theta dt, \tag{2}$$

where C is an arbitrary constant.

Usually Θ is given as a function of depth, so we can not directly integrate this equation by t. Now we are obliged to make clear some relationships between depth h and time t while we urge to integrate this equation.

On Fig. 1, we show results of some experiment of BT which is made on board of M.R.V. Ryofu Maru. This results show us that the submerging speed of BT depend only on the ship speed and may be regarded as uniform in the almost whole period of submerging. On the other hand, though it seems quite difficult to measure directly the surfacing speed of BT, we venture to assume

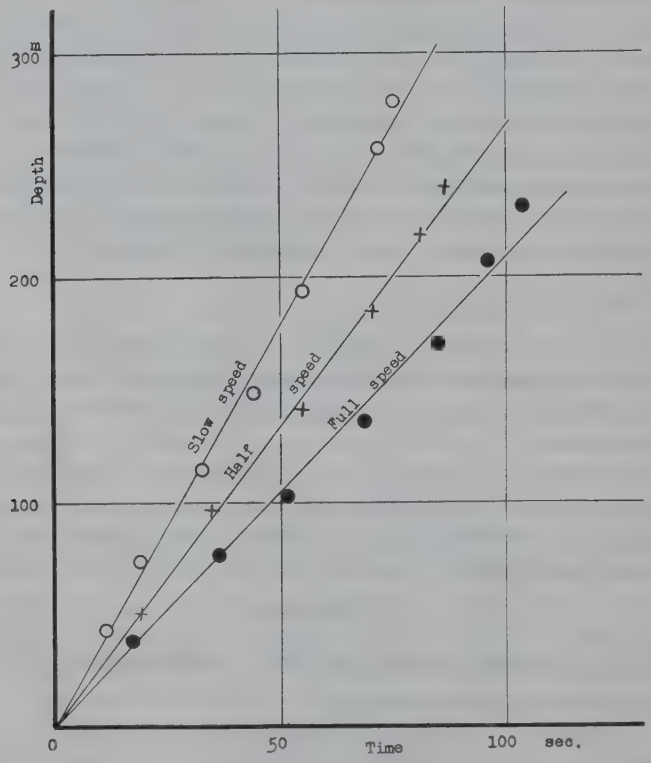


Fig. 1. Relationship between the depth and the time in which BT reaches to this depth, (without nose sleave, on board the Ryofu Maru)

the surfacing speed may also be constant by analogy with the case of submerging. Denoting submerging speed and surfacing speed of BT as α and β',

respectively, following two relations may be approximately satisfied;

$$h=\alpha t \qquad \text{in the period of submerging} \qquad (3)$$

$$h=h_0-\beta t \qquad \text{in the period of surfacing} \qquad (4)$$

where h_0 is the maximum depth at where BT is reached.

Substituting (3) into (2), we get,

$$\theta=Ce^{-\frac{\mu}{\alpha}h}+\frac{\mu}{\alpha}e^{-\frac{\mu}{\alpha}h}\int e^{\frac{\mu}{\alpha}h}\Theta dh. \qquad (5)$$

By means of integration by parts, we can obtain the folloging infinite series for θ,

$$\theta_1=Ce^{-\frac{\mu}{\alpha}h}+\Theta-\frac{\alpha}{\mu}\Theta'+\cdots\cdots+\left(-\frac{\alpha}{\mu}\right)^n\Theta^{(n)}+\cdots\cdots. \qquad (6)$$

In the region where this series converge, we may be able to compute the magnitude of θ for each depth. Then the successive argument is restricted only within the depth where the series converge. Usually, Θ is continuous and $\left|\frac{\alpha}{\mu}\right|$ may be less than unity, then the series converge, but if there is some layers in which Θ is not continuous, equation (6) can not be adopted.

Considering the initial conditions, we can decide C as the difference between temperatures in the atmosphere and the sea surface. But the terms including C soon become negligibly small when h increases. Then, from (6), omitting these terms, it follows that

$$\theta_1\simeq\Theta-\frac{\alpha}{\mu}\Theta'+\left(\frac{\alpha}{\mu}\right)^2\Theta''-\cdots\cdots+\left(-\frac{\alpha}{\mu}\right)^n\Theta^{(n)}+\cdots\cdots \qquad (7)$$

in the region excluding the vicinity of the sea surface.

Substituting (4) into (2), for the case of heaving, the integration by parts gives

$$\theta_2=De^{\frac{\mu}{\beta}(h-h_0)}+\Theta+\cdots\cdots+\left(\frac{\beta}{\mu}\right)^n\Theta^{(n)}. \qquad (8)$$

Considering the initial conditions, θ_2 must be equal to θ_1, at $h=h_0$. Then an arbitrary constant D is decided as follows:—

$$D=\left[\left(-\frac{\alpha}{\mu}-\frac{\beta}{\mu}\right)\Theta'+\left\{\left(\frac{\alpha}{\mu}\right)^2-\left(\frac{\beta}{\mu}\right)^2\right\}\Theta''+\cdots\cdots\right.$$
$$\left.+\left\{\left(-\frac{\alpha}{\mu}\right)^n-\left(\frac{\beta}{\mu}\right)^n\right\}\Theta^{n)}+\cdots\cdots\right]_{h=h_0}.$$

In layers below 250 m, according to our experiences the vertical gradient of water temperature may be expected to be small and to be almost constant.

Magnitude of exponential term decreases so quickly as h is smaller compared with h_0. Omitting first term, from (8), as the first approximation we get

$$\theta_2 \simeq \Theta + \frac{\beta}{\mu}\Theta' + \left(\frac{\beta}{\mu}\right)^2 \Theta'' + \cdots\cdots + \left(\frac{\beta}{\mu}\right)^n \Theta^{(n)} + \cdots\cdots. \tag{9}$$

For the thermal breadth of hysteresis on BT records at each depth, subtracting from (7), it follows that

$$\theta_1 - \theta_2 = \sum_n \left\{ \left(-\frac{\alpha}{\mu}\right)^{2n-1} - \left(\frac{\beta}{\mu}\right)^{2n-1} \right\} \Theta^{(2n-1)}. \tag{10}$$

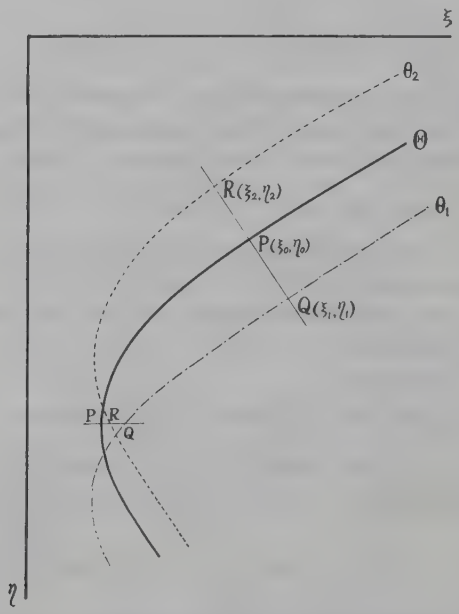


Fig. 2. Geometric schema of BT records diagram.

In Fig. 2, let $P(\xi_0, \eta_0)$ be a point on a curve in BT diagrams, which is represented by a equation $\theta = \Theta_{(h)}$, then $\eta_0 = \Theta_{(\xi_0)}$. The equation of the normal at (ξ_0, η_0) is

$$\theta - \Theta_{(\xi_0)} = -\frac{1}{\Theta'_{(\xi_0)}}(h - \xi_0) \tag{11}$$

from a well known formula of analytical geometry.

Let this normal through P meet two curves. The equations of two curves are $\theta=\theta_{1(h)}$ and $\theta=\theta_{2(h)}$, at $Q(\xi_1, \eta_1)$, $R(\xi_2, \eta_2)$ respectively.

$$\left.\begin{aligned}
\xi_1&=\xi_0-\frac{\alpha}{\mu}\Theta'^2+\left(\frac{\alpha}{\mu}\right)^2\Theta'\Theta''-\cdots\cdots+\left(-\frac{\alpha}{\mu}\right)^n\Theta'\Theta^{(n)}+\cdots\cdots\\
\xi_2&=\xi_0+\frac{\beta}{\mu}\Theta'^2+\left(\frac{\beta}{\mu}\right)^2\Theta'\Theta''+\cdots\cdots+\left(\frac{\beta}{\mu}\right)^n\Theta'\Theta^{(n)}+\cdots\cdots\\
\eta_1&=\eta_0-\frac{\alpha}{\mu}\Theta'+\left(\frac{\alpha}{\mu}\right)^2\Theta''-\cdots\cdots+\left(-\frac{\alpha}{\mu}\right)^n\Theta^{(n)}+\cdots\cdots\\
\eta_2&=\eta_0+\frac{\beta}{\mu}\Theta'+\left(\frac{\beta}{\mu}\right)^2\Theta''+\cdots\cdots+\left(\frac{\beta}{\mu}\right)^n\Theta^{(n)}+\cdots\cdots
\end{aligned}\right\} \tag{12}$$

Then it follows that

$$\frac{\overline{PR}}{\overline{PQ}}=\frac{\sum_n\left(\frac{\beta}{\mu}\right)^n\Theta^{(n)}}{\sum_n\left(-\frac{\alpha}{\mu}\right)^n\Theta^{(n)}}. \tag{13}$$

Strictly speaking, geometry on BT diagrams must be discussed in cylindrical coordinate system, but we have studied using orthogonal coordinate systems in the above arguments, principally by reasons of easiness of mathematical treatment. The torsion of coordinate on BT diagrams is practically not so large that error of the above obtained results may be regarded as negligible.

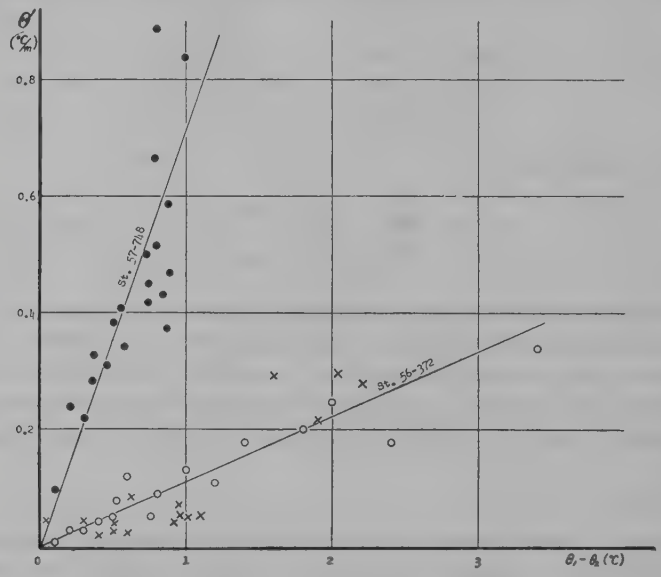
4. Numerical example

We have already pointed out that relationships between the time and the depth to which BT reaches are almost linear. From Fig. 1 we can determine values of α as 3.6 m/sec, 2.7 m/sec and 2.1 m/sec, for slow, half and full speed, respectively. To measure the surfacing speed β directly is so difficult that we are obliged to estimate β by means of dividing the maximum depth of BT by time which is needed for heaving up, then these may be 1.7 m/sec, 1.1 m/sec and 0.8 m/sec, respectively, on board of JMA RMV Ryofu Maru.

Thermal time constant $\frac{1}{\mu}$ is usually unknown, so we must also estimate this amount. In equation (10), if we substitute average value of derivatives of θ_1 and θ_2 for derivative of Θ, we can obtain rough value of μ. Assuming $\frac{\alpha}{\mu}\frac{\Theta^{(n+1)}}{\Theta^{(n)}}$ and $\frac{\beta}{\mu}\frac{\Theta^{(n+1)}}{\Theta^{(n)}}$ are less than unity, we may approximately calculate μ by the following formula.

$$\mu \simeq \frac{\alpha+\beta}{\theta_1-\theta_2}\Theta' \tag{14}$$

In Fig. 3, we show several examples of the relationships between the bredth of hysteresis of BT records and the temperature gradient. It shows us



○; St. 56-372, (slow ship speed, with nose sleeve). } Examples of linear relation.
●; St. 57-748, (full ship speed, with nose sleeve). } Examples of linear relation.
×; St. 58-807, (half ship speed, without nose sleeve). } Example of non-linear relation.

Fig. 3. Relationship between the thermal bredth of hysteresis and the vertical gradient of water temperature.

that though relations are sometimes complicated, but there may be very little misunderstanding to conclude that bredths are almost proportional to temperature gradient, as we expect from the formula (14). This may be reasonable support for justification of our assumption.

By the way, values of μ computed with (14) are about 0.4 and 3.0 sec^{-1} at St. 56-372 and St. 57-748 respectively. Then, it is presumed to us that though

different values of μ are obtained for different ship speeds and different instruments, usually uniformity against depth is rather good in a period of observations.

Although formula (13) and the process, by which (13) is derived, suggest us a method of reading of BT records, but (13) is too complicated to compute this ratio for every observation. Usually the ratio between differential coefficients of successive orders is ordinarily less than 1/5. Then it is sufficient to take the derivative of the first order. Neglecting terms including derivatives of higher orders of (13), it follows;

$$\frac{\overline{PR}}{\overline{PQ}} = \simeq -\frac{\beta}{\alpha}. \tag{15}$$

Negative sign in the above equation represents that two curves of hysteresis lie in opposit sides of a curve which shows vertual temperature distribution each other; θ_1, is in warmer and θ_2 is in colder side when Θ' is negative and they are in contrary when Θ' is positive from (7) and (9).

Sometimes we meet encounter thermal inversion layer in which maximum or minimum temperature is observed, and in neighbourhood of the depth of maximum or minimum the first derivative vanishes or is smaller than second derivative. In this case, the following formula is more suitable than (15),

$$\frac{\overline{PR}}{\overline{PQ}} \simeq \left(\frac{\beta}{\alpha}\right)^2. \tag{16}$$

Positive sign represents that two curves lie in the same side; in colder side when Θ'' is positive or maximum is there and in warmer side when minimum is there.

Sometimes we meet thermally homogeneous layers of finite thickness in which all derivatives of Θ vanish out. In this case, though the ratio of (13) is indefinite, practically there will be no trouble because two curves coinside and hysteresis disappear in this layer.

5. *Conclusions*

(1) The principal cause of hysteresis on BT records may be the time lag of thermal sensitive apparatus and its magnitude is mainly affected by dimensions of capillary tube and submerging speed of instruments.

(2) On reading BT records, reasonable method is following;— draw temporary curve, lines normal to this curve intersect two curves of hysteresis.

Connecting points dividing distances between these two hysteresis curves proportional to $-\beta/\alpha$ when Θ' is not 0, we may approximately obtain vertual distribution curve of temperature. When Θ' is almost equals to 0, we may apply the discussion of the previous section.

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Tidal Analysis and Prediction by using the Electronic Computer

By

Masamori Miyazaki and Takeo Ueno

Japan Meteorological Agency

1. Introduction

Tidal analysis is one of the most labourous works in the field of geophysics. Various methods have been proposed and actually used for this purpose, but most of them are planned to be computed by hands. At least two or three months are required for the hand analysis of one year records even when they are carried out by skilled workers.

It is possible to make execute these computations by the automatic computers. A few years ago, the use of the punching machine was tried in our office for this purpose. The T.I. method was used in this case. Similar trials by using various methods were also made in some of other countries. We find from these results that the machine work surely enables us to decrease the time and labour involved in the computations. However, the basic methods are essentially of the hand-work type, and are planned to be convenient for the hand analysis. Therefore, it will be rather natural that the procedures are often very much complicated when we carry out them by the machine.

Recently, Miyazaki (1958) proposed a new method which is convenient for the analysis by automatic computers as well as the hand analysis. This method was tested at several ports along the Japanese coasts, and it was proved that the time required was only within a few hours per station when we make use the punching machine, and that the results were nearly as accurate as those given by the T.I. method.

By using this method, we have made a program to be executed by the electronic computer IBM 704. The Fortran system has been used for this purpose. We shall describe the details on this program in this manuscript.

In contrast with the case of analysis, the tidal prediction is not so labourous task in the present time, but is still fairly time taking. A special type of harmonic composers, the tide predictor, is now widely used for this purpose, when the tidal constants are given at any station, the predicted curve for one year will be drawn in about three or four hours by this machine. But, the reading of curves, and other hand works will require fair additive hours.

Above procedure is now carried out as the routine works in many of the countries, and the time and labour involved in them will be not negligible. Thus, the use of the automatic computers have been tried by some authorities, and is proved to be very useful. We now write a program for the tidal prediction, which enables us to obtain the final tables and hourly predictions by only giving the station longitude and the year to be predicted as the variable data. We shall also explain this program in this manuscript.

2. *Outline of the program*

In this program, we can make use any combinations of the constituents, so long as the total number of them does not exceed 60. The analysis is usually made for 60 constituents, and the prediction is given by using 15 to 45 constituents.

The program consists of three steps. The tidal analysis is carried out by combining the first and second step of them, and the prediction is carried out by combining the first and third step of them, respectively. The outline of the procedure in each step is as follows.

First step.

We first make read the epoch of computation and the universal constants of constituents, and then compute f and $V+u$ for each of them. The computations are made by DOODSON's method.

Second step.

We make read the necessary observed data for any station, perform the 240 term harmonic analysis by using these data, and compute the final constants according to MIYAZAKI's method. The results are tabulated on the magnetic tape.

Third step.

Firstly, we make the sine table of 0.1 degree interval in the core storage, and then read the tidal constants for any station. Next, we compute the hourly tide levels by combining the sinusoidal oscillations which correspond to the constituent tides adopted in the first step.

The high and low waters are given from the interpolations of three consecutive hourly values. The hourly predictions and tide tables are transferred to two units of the magnetic tape.

Timing.

The machine time of computation is about one minute for the analysis, which is nearly independent of the number of constituents. It is about 5 to 10 minutes for the prediction when 15 to 40 constituents are counted in.

3. *Input data*

The following cards are to be punched before computations. The formats of cards are shown in the program.

H1.....One card. The heading card in the first step. On this card, we shall punch the epoch of computation, and the number of constituents n to be counted in.

H2.....One card. The heading card in the second step. The station number and longitude are to be punched.

H3.....One card. The heading card in the third step. The height of the mean sea level above datum is added to the content of H2.

N1.....n cards. The necessary coefficients and constants of n constituents are punched here.

N2.....8 cards. Coefficients of f and u are punched for eight representative constituents.

N3.....10 cards. The 35.5 hourly readings of the tide level are punched here.

N4.....25 cards. Here punched are the combinations of the selected hourly readings of the tide levels, from which the 35.5 hourly values are computed in the machine.

N5.....n/5 cards. The accurate speed of each constituent is punched in them.

N6.....n/5 cards. The tidal constants are punched here.

The card deck H1, N1, N2, H2, and N3 (or N4) are necessary for the tidal analysis, and the deck H1, N1, N2, N5, H3, and N6 are necessary for the tidal prediction, respectively. In the case of the consecutive analysis or prediction for the common epoch, the deck of N3 (N4) or N6 is to be renewed per station.

4. Output data

The output data are given on the magnetic tape by our program. The printing of these results are usually carried out by the high-speed printer, which is used as the off-line apparatus.

The tidal constants will be tabulated in the final print in 1/10 cm, and 1/100 deg. The hourly predictions are given in cm, and tide tables are given in min. and cm units, respectively.

The name of each constituent is shown in the table of tidal constants by the order of harmonics, which is proper to each constituent. They are shown in Table 1.

In our tide tables, we sometimes find the apparent high or low waters at $50^h\ 0^m$, whose heights are always zero. They are of course not present actually, and only remained for the purpose of machine time saving. The high and low waters can be tabulated at most three times a day, respectively.

5. Procedure

In the first step we shall compute the equilibrium arguments of constituents V, v, and f for the epoch. The argument V is given by

$$V = s \cdot C_s + h \cdot C_h + p \cdot C_p + C_e , \qquad (1)$$

where s, h are the mean longitudes of moon and sun, and p is the mean longitude of moon's perigee. C_s, C_h, and C_p are given integers, and C_e is the given angle, which are all proper to the constituents.

The coefficients C_s, C_h, C_p, and C_e are given in input cards, and s, h, and p are computed in the machine for the epoch. The argument V is then easily computed from formula (1).

Arguments f and u are usually given from the following formulas

$$\left.\begin{aligned} f &= \sum_{k=0}^{3} f_k \cos kN, \\ u &= \sum_{k=1}^{3} u_k \sin kN, \end{aligned}\right\} \qquad (2)$$

for representative constituents, where N is the mean longitude of moon's ascending node at the center of the period. Coefficients f_k, u_k are punched in cards N2, and N is computed in the machine.

The formulas (2) are computed for eight constituents Mm, Mf, O_1, K_1, J_1, O_1, M_2 and K_2, respectively. f and u for other original constituents are equal to one pair of them. Those for the compound constituents are given by combining them by the following formulas

$$\left.\begin{aligned} f &= f_i \cdot f_j, \\ u &= u_i \pm u_j, \end{aligned}\right\} \qquad (3)$$

where the suffices i, j represent the arguments of original constituents which form the compound ones.

The argument computations for M_1 and L_2 constituents are not given by the above method. They are to be computed from the special formulas containing p and N, which were already given by Doodson (1928).

The procedure in the second step is based on Miyazaki's method. When the 240 term harmonic analysis is made for the tidal records of 355 (mean solar) days, almost all constituents are separated approximately from each other. The 35.5 hourly readings are used for this purpose. When the hourly values are only available in this case, the intermediate values are to be interpolated from hourly values before and after them. In our program, we can read either type of records in the core strage.

The harmonic analysis of 240 terms are given by

$$\left.\begin{aligned} a_i &= \sum_{k=0}^{239} H(k) \cdot \left[\frac{1}{120} \cos\left(\frac{2\pi k \cdot i}{240}\right)\right], \\ b_i &= \sum_{k=1}^{239} H(k) \cdot \left[\frac{1}{120} \sin\left(\frac{2\pi k \cdot i}{240}\right)\right], \end{aligned}\right\} \qquad (4)$$

where $H(k)$ is the 35.5 hourly readings which are given from N3 or N4. Numerical values in the brackets are computed and stored in the core at the beginning of the second step.

After the harmonic analysis is performed, small corrections are necessary

in order to compute the exact constants of tide. The coefficients of corrections are read from cards N1 in the first step.

The larger part of the procedure in the third step consists of the hourly predictions and making tide tables. The hourly predictions are given by the formula

$$h(t)=H_0+\sum_{k=1}^{n} f_k H_k \cos(a_k \cdot t+V_k+u_k-\kappa_k) , \qquad (5)$$

where

$h(t)$; the hourly predictions of the sea level. t is the time in hours counted from the epoch.

H_0 ; datum line of the sea level below the mean value.

V_k, f_k, u_k ; equillibrium arguments of the constituents at the epoch (V_k) or at the center of prediction (f_k, u_k), respectively.

H_k, κ_k ; tidal constants of each constituent.

a_k ; the hourly speed of each constituent.

In this formula, V_k, f_k, and u_k are computed in the first step, and H_0, H_k, κ_k, and a_k are read from cards N5 and N6 in this step.

The high and low waters are interpolated from three consecutive $h(t)$ values by using the cubic formulas. Provided that $h(t_0)$ is a maximum or minimum value in the sequence of $h(t)$, the high or low water will exist near the time t_0. The time difference Δt from t_0 will be given by

$$\Delta t=\frac{h(t_0-1)-h(t_0+1)}{2\{h(t_0-1)-2h(t_0)+h(t_0+1)\}} , \qquad (6)$$

and the height of the high or low water will be given by

$$h_m=h(t_0)-\frac{1}{2}(\Delta t)^2 \cdot \{h(t_0-1)-2h(t_0)+h(t_0+1)\} , \qquad (7)$$

respectively.

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DOODSON, A.T. (1928): The analysis of tidal observations. Phil. Trans. Roy. Soc. Lond., A 227, p. 223-279.

MIYAZAKI, M. (1958): A method for the harmonic analysis of tides. *Oceanogr. Mag.*, 10 (1), p. 65-80.

Table 1. Order of harmonics i for each constituent in the 240 term analysis

Const.	Order	Const.	Order	Const.	Order
A_0	0	ϕ_1	118	$2SM_2$	14
Sa	1	J_1	129 (111)		
Ssa	2	SO_1	140 (100)	MQ_3	43
Mm	13	OO_1	142 (98)	MO_3	56
Msf	24	γ_1	155 (85)	M_3	69
Mf	26			SO_3	80
Mt	39	OQ_2	167 (73)	MK_3	82
		δ_2	169 (71)	SP_3	104
α_1	53	$2N_2$	180 (60)	SK_3	106
$2Q_1$	64	μ_2	182 (58)	K_3	108
δ_1	66	N_2	193 (47)		
Q_1	77	ν_2	195 (45)	MN_4	159 (81)
ρ_1	79	OP_2	204 (36)	M_4	172 (68)
O_1	90	ε_2	205 (35)	SN_4	183 (57)
MP_1	92	M_2	206 (34)	MS_4	196 (44)
β_1	101	ζ_2	207 (33)	MK_4	198 (42)
M_1	103	λ_2	217 (23)	S_4	220 (20)
χ_1	105	L_2	219 (21)	SK_4	222 (18)
π_1	113	T_2	229 (11)		
P_1	114	S_2	230 (10)	M_6	138 (102)
S_1	115	R_2	231 (9)	$2MS_6$	162 (78)
K_1	116	K_2	232 (8)	$2SM_6$	186 (54)
ψ_1	117	η_2	5		

Remark: Capital numbers in parentheses are the complementary orders ranging from 0 to 119.

Table 2a. Flow chart of the program (First step)

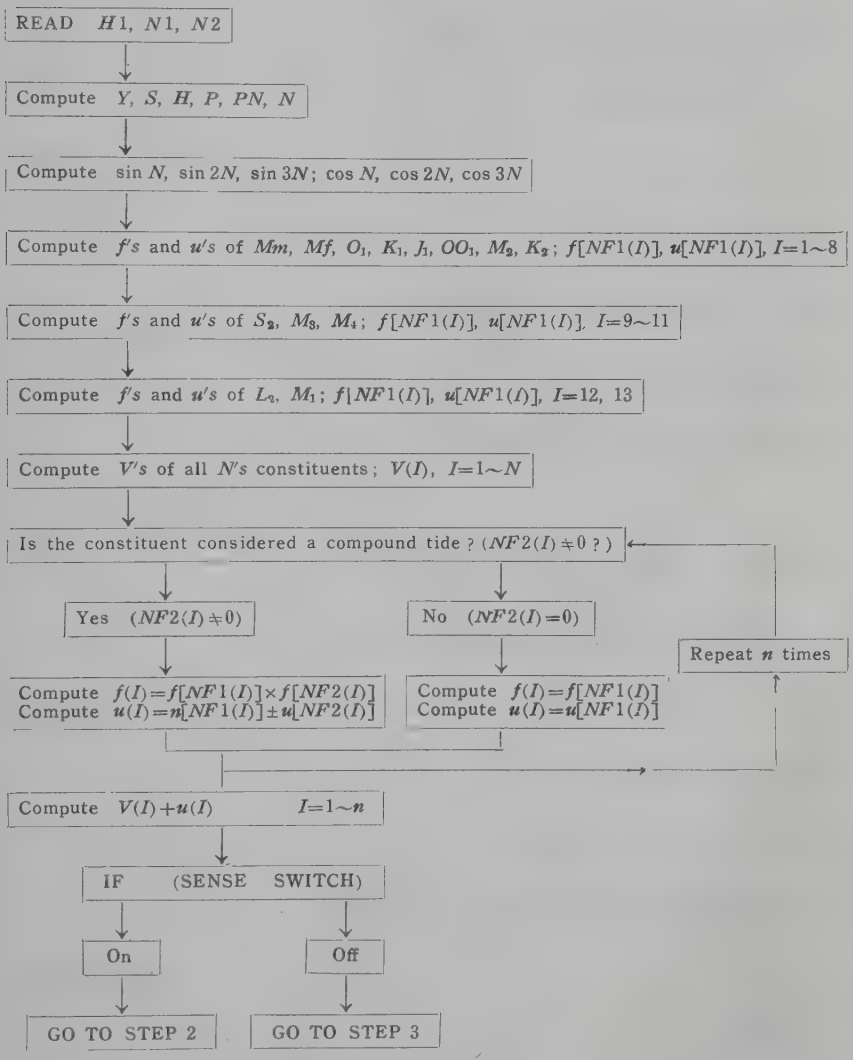

READ $H1$, $N1$, $N2$
Compute Y, S, H, P, PN, N
Compute $\sin N$, $\sin 2N$, $\sin 3N$; $\cos N$, $\cos 2N$, $\cos 3N$
Compute f's and u's of Mm, Mf, O_1, K_1, J_1, OO_1, M_2, K_2; $f[NF1(I)]$, $u[NF1(I)]$, $I=1\sim8$
Compute f's and u's of S_2, M_3, M_4; $f[NF1(I)]$, $u[NF1(I)]$, $I=9\sim11$
Compute f's and u's of L_2, M_1; $f[NF1(I)]$, $u[NF1(I)]$, $I=12, 13$
Compute V's of all N's constituents; $V(I)$, $I=1\sim N$
Is the constituent considered a compound tide ? ($NF2(I)\neq0$?)
Yes ($NF2(I)\neq0$)
No ($NF2(I)=0$)
Repeat n times
Compute $f(I)=f[NF1(I)]\times f[NF2(I)]$
Compute $u(I)=n[NF1(I)]\pm u[NF2(I)]$
Compute $f(I)=f[NF1(I)]$
Compute $u(I)=u[NF1(I)]$
Compute $V(I)+u(I)$ $I=1\sim n$
IF (SENSE SWITCH)
On
Off
GO TO STEP 2
GO TO STEP 3

Table 2b. Flow chart of the program (Second step)

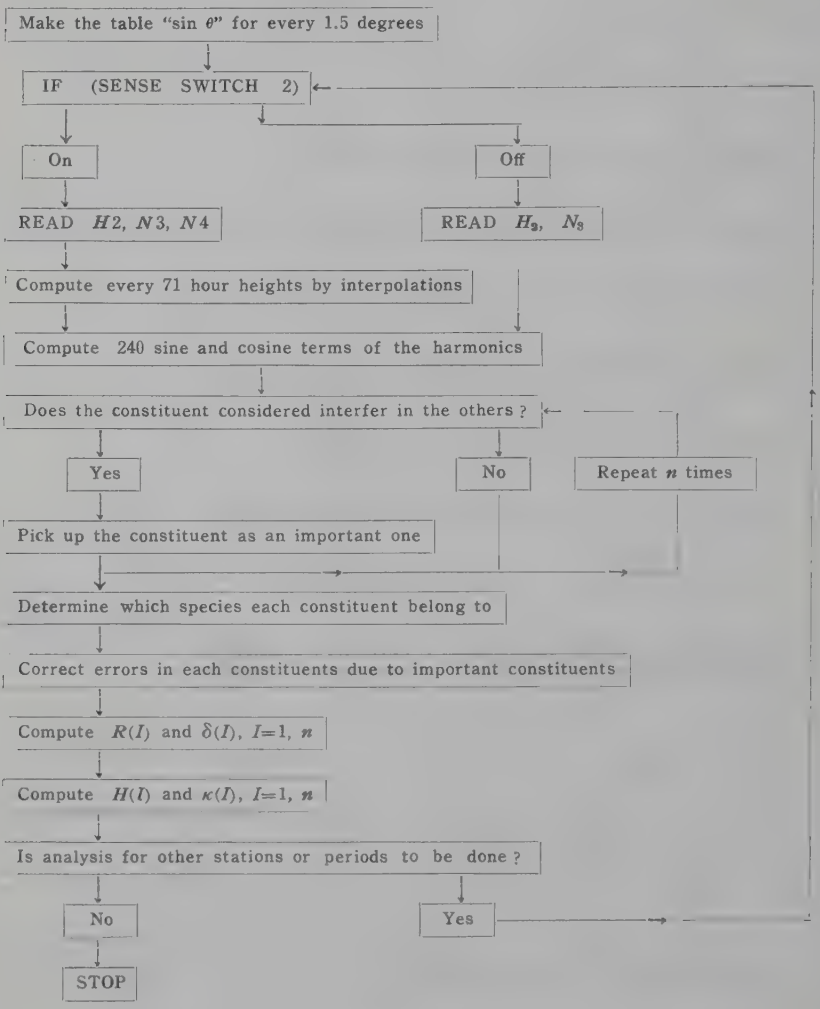
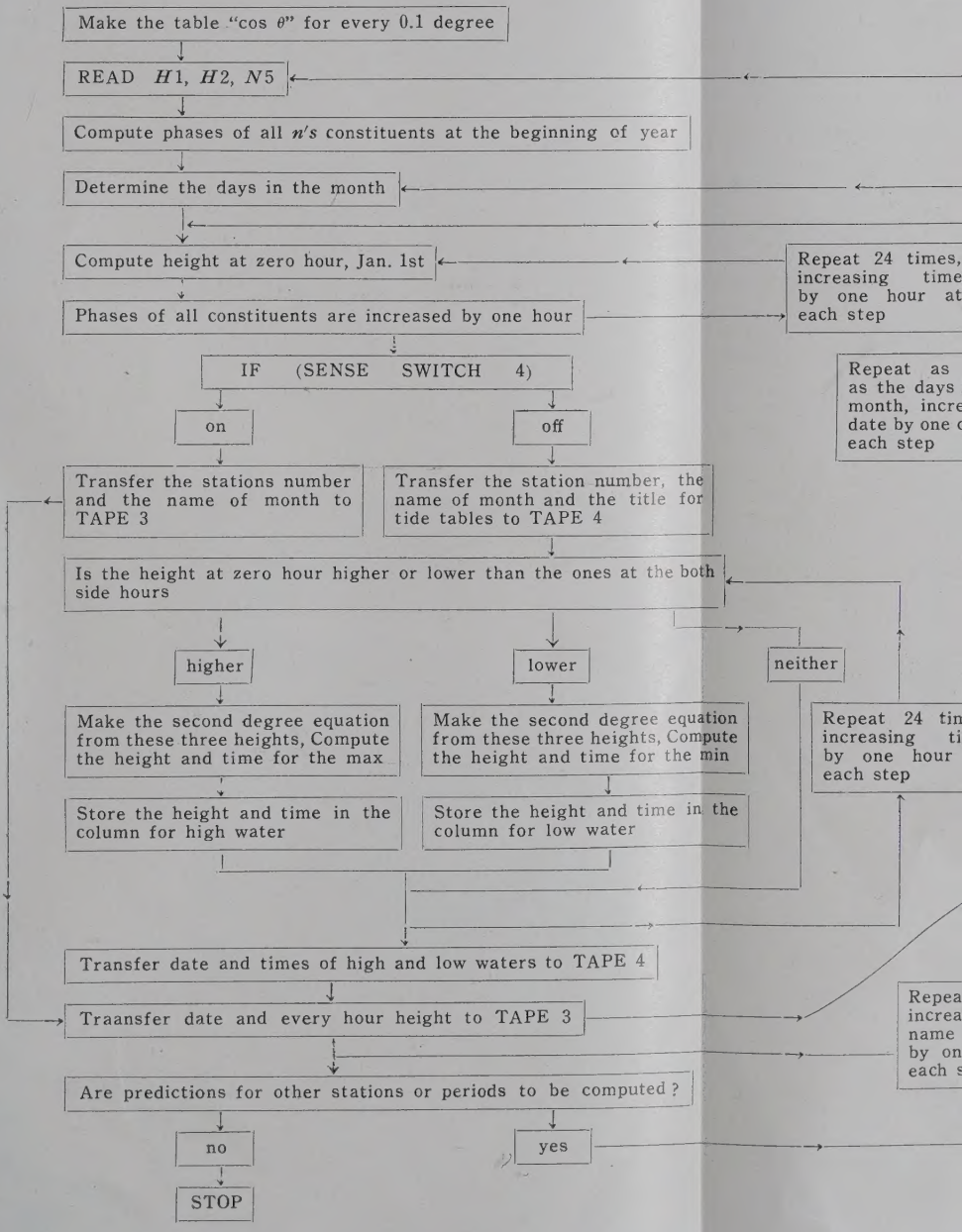

Make the table "sin θ" for every 1.5 degrees
IF (SENSE SWITCH 2)
On
Off
READ H2, N3, N4
READ H3, N3
Compute every 71 hour heights by interpolations
Compute 240 sine and cosine terms of the harmonics
Does the constituent considered interfer in the others ?
Yes
No
Repeat n times
Pick up the constituent as an important one
Determine which species each constituent belong to
Correct errors in each constituents due to important constituents
Compute R(I) and δ(I), I=1, n
Compute H(I) and κ(I), I=1, n
Is analysis for other stations or periods to be done ?
No
Yes
STOP

Table 2c. Flow chart of the program (Third step)


Make the table "cos θ" for every 0.1 degree
READ H1, H2, N5
Compute phases of all n's constituents at the beginning of year
Determine the days in the month
Compute height at zero hour, Jan. 1st
Repeat 24 times, increasing time by one hour at each step
Phases of all constituents are increased by one hour
IF (SENSE SWITCH 4)
Repeat as as the days month, incre date by one c each step
on
off
Transfer the stations number and the name of month to TAPE 3
Transfer the station number, the name of month and the title for tide tables to TAPE 4
Is the height at zero hour higher or lower than the ones at the both side hours
higher
lower
neither
Make the second degree equation from these three heights, Compute the height and time for the max
Make the second degree equation from these three heights, Compute the height and time for the min
Repeat 24 tin increasing ti by one hour each step
Store the height and time in the column for high water
Store the height and time in the column for low water
Transfer date and times of high and low waters to TAPE 4
Traansfer date and every hour height to TAPE 3
Repea increa name by on each s
Are predictions for other stations or periods to be computed ?
no
yes
STOP

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